INTRODUCTION TO THE USE OF SONAR SYSTEMS FOR ESTIMATING FISH BIOMASS

by

J. Burczynski*
Fishery Resources and Environment Division

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
1982

The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

M-42
ISBN 92-5-101161-3

PREPARATION OF THIS PAPER

This paper provides an introduction to certain aspects of acoustic surveys of fish stocks; namely, the general structure and functioning of sonar systems, and how echoes returned by fish are processed to measure fish abundance. It aims to convey an understanding of the basic principles and problems involved rather than detailed guidance on how to adjust and operate acoustic systems (although a summary of a system performance check is included to give an idea of the amount and kind of work needed).

The paper has been critically reviewed and edited by Dr. W.G. Clark. Further advice on the content and organization of the text has been received from Dr. G.P. Bazigos, Dr. J.A. Gulland and Mr. K.A. Johannesson.

This is the second issue which has been revised and corrected by the author following receipt of comments from various researchers working in fishery acoustics. In particular, detailed comments and suggestions were received from Mr. R.E. Craig and Mr. R. Mitson.

*Present address of author: Morski Instytut Rybacki, Al. Zjednoczenia 1, 81-345 Gdynia, Poland.

Distribution:

FAO Fisheries Department
FAO Regional Fishery Officers
FAO Fishery Projects
Specialised Institutes and
  Individual Scientists
Selector SM

For bibliographic purposes this document should be c ted as follows:

Burczynski, J., Introduction to the use of
1982 sonar systems for estimating fish biomass. FAO Fish.Tech.Pap., (191)Rev.1:89 p.

ABSTRACT

This manual of sonar systems is mainly intended to assist fishery biologists, participating in FAO projects, in understanding the basic principles and problems involved in estimating fish biomass and determining the spatial distribution of fish. The manual is divided into 3 parts. The first part is a general description of the sonar system as a means for fish detection and biomass estimation. The second part deals with elementary acoustics, and particularly with the propagation of acoustic waves, transducers, reflection by single and multiple targets, refraction and deflection of sound in the sea and the acoustic properties of fish. The third part discusses how quantitative information on fish is obtained by echosounding with particular reference to the time varied gain, the effect of the directivity pattern, the echo integrator and the calibration. Illustrative diagrams accompany the text throughout the manual. A summary of a system performance check is included in the appendix.

PREFACE

The aim of this manual is to describe how a sonar system functions and how to use it for estimating fish biomass and determining the spatial distribution of fish. The manual is intended mainly for fishery biologists working in FAO projects. However, it can be used by other specialists as an introduction to this subject. The material presented in this manual is rather descriptive and illustrative, and mathematics have been kept to a minimum.

The accompanying illustrations support the discussion and the basic equations in the text; however, relevant equations are inserted into some figures as well (e.g. Figures 20, 21, 22 and 24). For preliminary study, a reader can obtain a general idea about the phenomena being discussed in the text (i.e. the description and basic formula given there) by examining only the diagram presented in the corresponding figure. For a more thorough study, one can find the supporting mathematics given in detail on the figure to the side of the diagram.

Although the decibel units are in common use in acoustics, the material is presented here in a different form. For the reader who is not used to decibel units it will be much easier to understand the principal laws of acoustics if they are presented in the form of simple ratios than to first learn and get used to the new concept of decibel units and afterwards to learn the general laws of acoustics. (The concept of "decibel units" is explained in Appendix II.)

SYMBOLS AND ABBREVIATIONS

A : slope of the regression line

B : intercept of the regression line

b; b (ϕ, θ); b (Ω) : one-way directivity pattern function of a transducer

b^2; b^2 (ϕ, θ); b^2 (Ω) : two-way directivity pattern function of a transducer

b_0; b_0 (ϕ, θ) : value of one-way directivity pattern function of a transducer on the direction of its acoustic axis (the normalized value $b_0 = 1$)

b_f, b_f (ϕ, θ) : reflecting directivity pattern of a fish

C : proportionality coefficient in the echo integrator equation (65)

C^x : calibration constant of an integrator system (equation 66)

c : sound velocity

CRT : Cathode Ray Tube (display)

d : biomass density (i.e. density of fish in units of weight per unit area)

dB : decibel

ESDU : Elementary Sampling Distance Unit

f : frequency

I : sound intensity

I_0 : intensity of sound radiated by a source

I_e : intensity of an echo in the neighbourhood of the transducer

I_i : intensity of an incident sound wave (against a target or targets)

I_r : intensity of reflected sound wave (by a target or targets)

j, m : index numbers (1, 2, 3 ...)

L : fish length

M : integrator deflection (output)

N, n : number of targets (fish)

n.mi : nautical mile

P : power

p : pressure

R : distance

r : correlation coefficient

S, s : area

s : salinity

T, t : time

t : temperature

TS : Target Strength

ts : ratio between intensities of an incident and reflected sound

TVG : Time Varied Gain

u : voltage

u_e : voltage on the transducer's terminals or on the echosounder's output generated by an echo

V, v : volume

w : fish weight

α : attenuation coefficient of sound

β : logarithmic decrement of attenuation of sound

Δ : increment (e.g. incremental volume Δv)

ϕ, θ : plane angle

λ : wavelength

μ : reflection index

ν : density of the medium

ρ : density of targets (number of fish per unit volume)

σ : equivalent cross-section of a target (scattering cross section)

τ : pulse duration

ψ : equivalent beam width of a transducer

Ω : solid angle

$\sim$: sign of proportionality

CONTENTS

LIST OF FIGURES

1. THE SONAR SYSTEM AS A MEANS FOR FISH DETECTION AND BIOMASS ESTIMATION

1.1 The Sonar System

Generally speaking, a sonar system (sonar is an abbreviation for SOund NAvigation and Ranging) is an apparatus used for obtaining information about underwater objects and events by transmitting sound waves and observing the returned echoes. The sound waves produced by echosounders and sonars used for fish detection and biomass estimation are of the same nature as those produced by musical instruments, moving vehicles, human speech organs, etc. However, the human ear has a restricted range of perception of sound, limited approximately to frequencies between 16 and 20 000 Hertz (cycles per second, abbreviated Hz). Sonar systems used in fisheries work produce ultrasounds, i.e. sounds with a frequency usually ranging from 20 000 to 500 000 Hz (i.e. 20 to 500 kHz) which are not detectable by the human ear.

An apparatus used for the detection and investigation of underwater targets by means of transmitted sounds and returned echoes is called an active sonar system or simply a sonar system.1/ The users of sonar systems i.e. sailors, fishermen and marine researchers have adopted the following terms:

- a system that transmits vertically is called an "echosounder" (Figure 1a)
- a system that transmits horizontally is called a "sonar" (Figure 1b)

The functioning of both kinds of apparatus is the same. Therefore when discussing the basic theory of acoustics the functioning of acoustic equipment in general we will use the term "sonar system", and when discussing the practical use of a particular kind of equipment we will use one of the customary names, i.e. "echosounder" or "sonar".

The operation of sonar systems used in fisheries work is quite simple (see Figure 2). Sound is generated in discrete pulses, and after each pulse the system waits for a certain period to receive echoes from any targets in the insonified volume of water. A pulse is generated when a timer (usually part of the display device) activates an electrical transmitter for a fixed period of time. The electrical oscillation of the transmitter is converted mechanically into pressure oscillations (i.e. sound waves) in the water at the vibrating face of the transducer, which continues to generate sound until the timer switches off the transmitter. The result is a sound pulse of a certain duration travelling through the water away from the face of the transducer. Any target (e.g. fish) in the path of this pulse will return an echo to the transducer, which in the waiting mode performs the reverse of its function in the transmitting mode, i.e. it converts pressure oscillations at its face (the echo) into electrical oscillations that are picked up by a receiver, amplified, and converted into some visible sign on the display device, normally a paper recorder or an oscilloscope screen (see Figures 3 and 4).

Some technical terms are customarily used in describing the operating characteristics of sonar systems. The <u>frequency</u> (or working frequency) is the frequency of oscillation of the transducer in the transmitting mode, and consequently also of the sound waves generated in the water. Usually this is 38 kHz or 120 kHz. The <u>pulse repetition rate</u> is the number of of pulses (or transmissions) sent out per unit time, which may be ten to one hundred per minute depending on depth or distance to be covered. The <u>pulse duration</u> is the time interval during which the transducer actually vibrates in generating each pulse, typically about one millisecond. Thus when a transducer is operating at a pulse repetition rate of sixty transmissions per minute or one transmission per second, it generates sound for one millisecond in the transmitting mode, then waits for 999 milliseconds in the receiving mode, then generates the next one-millisecond pulse and so on. Since the speed of sound in seawater is roughly

1/ An apparatus used only for receiving the sounds generated by underwater objects is called a passive sonar system. Passive sonar systems are utilized in marine biology for detecting sounds generated by fish and other aquatic animals.

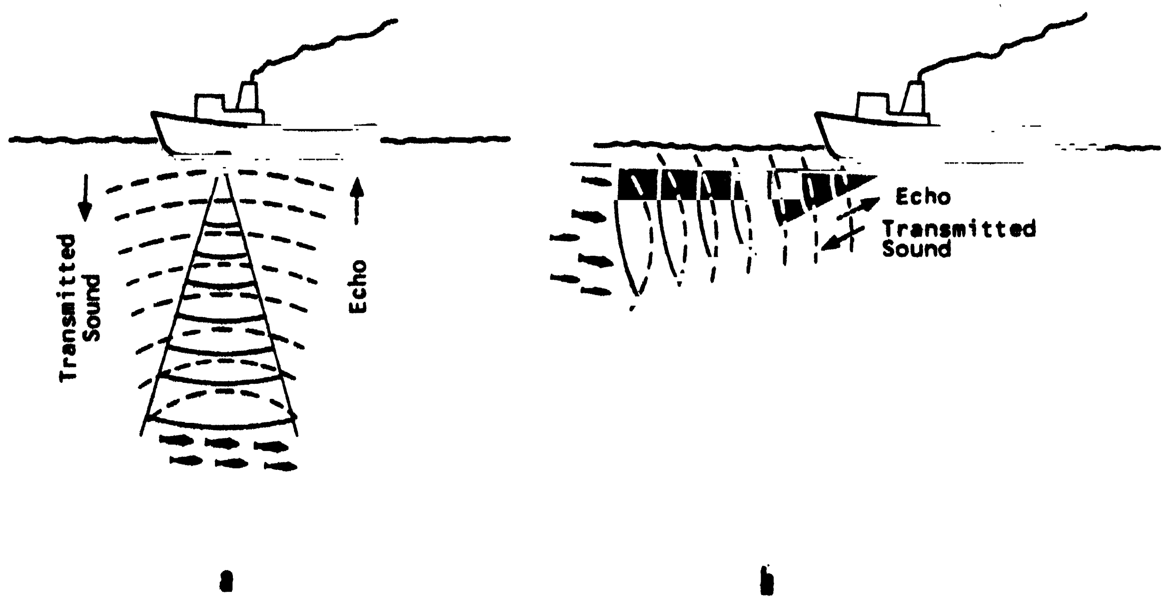


Figure 1   Detection and location of fish by
(a) echosounder (b) sonar

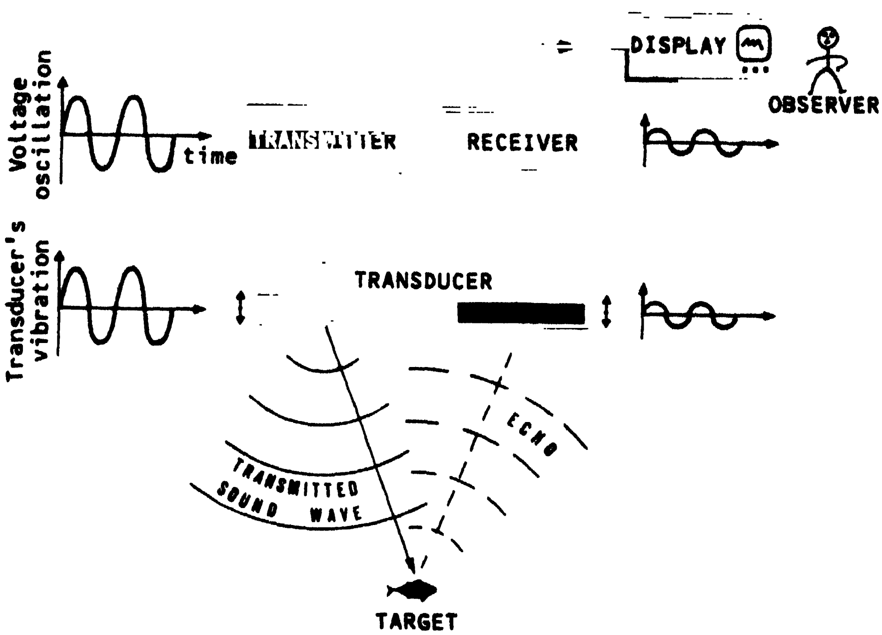


Figure 2   Functioning of an active sonar system

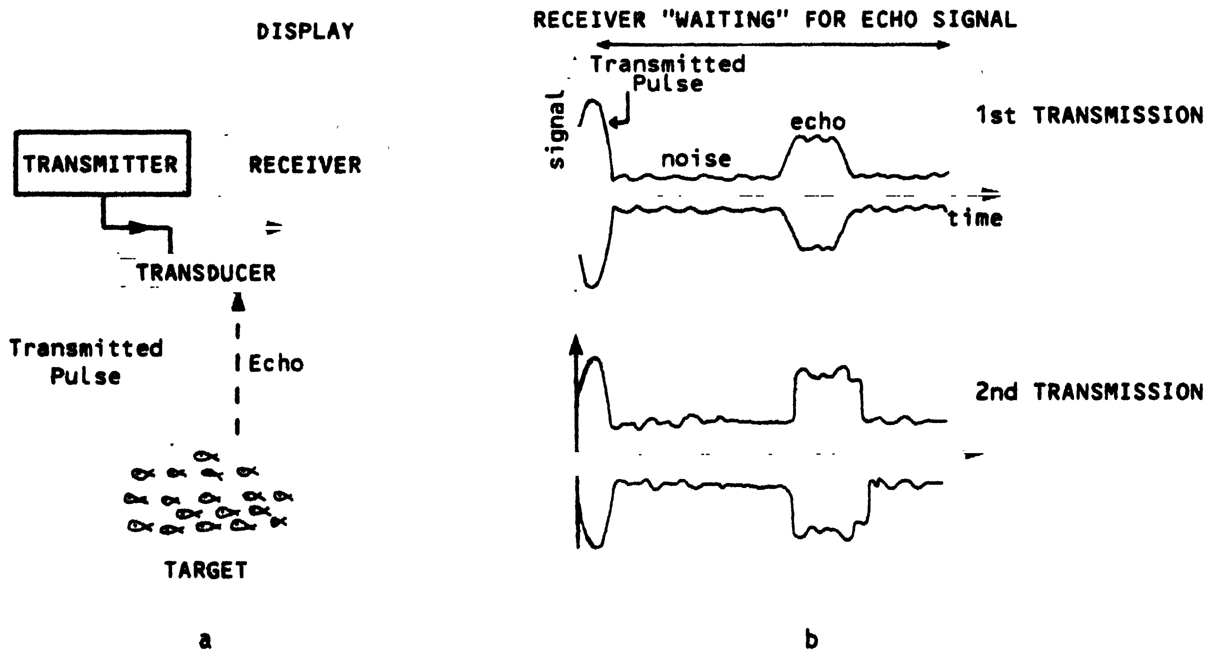


Figure 3 The pulse sonar system
(a) structure of a sonar system
(b) form of the transmitted pulse and echo signal on CRT display

constant at 1 500 metres per second, the pulse length, or thickness of the pulse travelling through the water, can be calculated from the pulse duration - a one-millisecond pulse will have a pulse length of about 1.5 m.

The processing of echoes returned by a target requires translating the reflected sound wave that reaches the transducer face, into a form suitable for obtaining information about the target. For example, one important piece of information to be obtained from echo sounding is the presence or absence of targets. The presence of a target gives a high peak of voltage on the transducer's terminals, and then at the receiver's, compared with a low background voltage, and it can be observed as a peak on the oscilloscope display, or a dark mark on the recorder paper (Figure 3b and 4). (The background voltage is the electrical noise or static inherent in the system. It is usually called self-noise).

Assuming that the sound velocity in seawater is a known constant, we can obtain another item of information about the target, namely the distance between the target and transducer (called the range), by measuring the time interval between transmitting pulse and receiving the echo from the target. Let us denote the distance between the target and the transducer by "R" (Figure 4). The sound pulse travels from the transducer to the target and back, so it covers the distance "R" twice. Therefore we can write that twice the distance transducer/ target or 2R is equal to the velocity of sound in seawater denoted "c", times the interval of time "t" between transmitting the pulse and receiving the echo:

$$2R = ct$$

By simple transformation of the above equation we obtain the formula for calculating the range of the target:

$$R = \frac{ct}{2} \tag{1}$$

In commercial echosounders and sonars the stylus of the paper recorder moves across the recording paper at a constant speed (Figure 4), while the paper is pulled under it also at a constant rate. When the stylus passes the "zero line" the triggering contact triggers the transmitter, which transmits the pulse into the water via the transducer. At the same moment the triggering contact also starts the time base of the oscilloscope display, which causes the movement of the electronic beam on the screen from its "zero position" downward at a constant speed. The receiver then waits (or listens) for an echo signal, and when the echo signal appears on the transducer's terminals in the form of a voltage increase it is amplified by the receiver and sent to the display unit. The voltage increase causes the recorder stylus to produce a dark mark on the recording paper which is called an echo trace. It can also be observed on the screen of the oscilloscope as a high peak voltage.

Because both the recorder's stylus and the electronic beam on the oscilloscope screen move at a constant, known speed we can calculate the time interval "t" between transmitting the pulse and receiving the echo, by measuring the distance between the zero line and the echo trace on the recording paper, or between the zero position and the peak voltage on the oscilloscope. Therefore we can calculate the range of the target from equation (1). In fact the scales of commercially-produced sonar and echo sounder displays, i.e. recorders and oscilloscopes, are simply marked in range units (metres or fathoms).

From the same simple display units such as a recorder and oscilloscope we can obtain even more information on the target. If it happens that both a small target and a large target of the same acoustic reflecting properties (e.g. two fish of the same species but different in size) appear at nearly the same range it is obvious that the small target will return a smaller echo than the bigger one. The small target will produce a rather thin and light echo trace on the recording paper, and a small peak on the oscilloscope, while the big target will produce a very dark echo trace on the recording paper and a high peak on the oscilloscope. But this kind of information is qualitative rather than quantitative. More

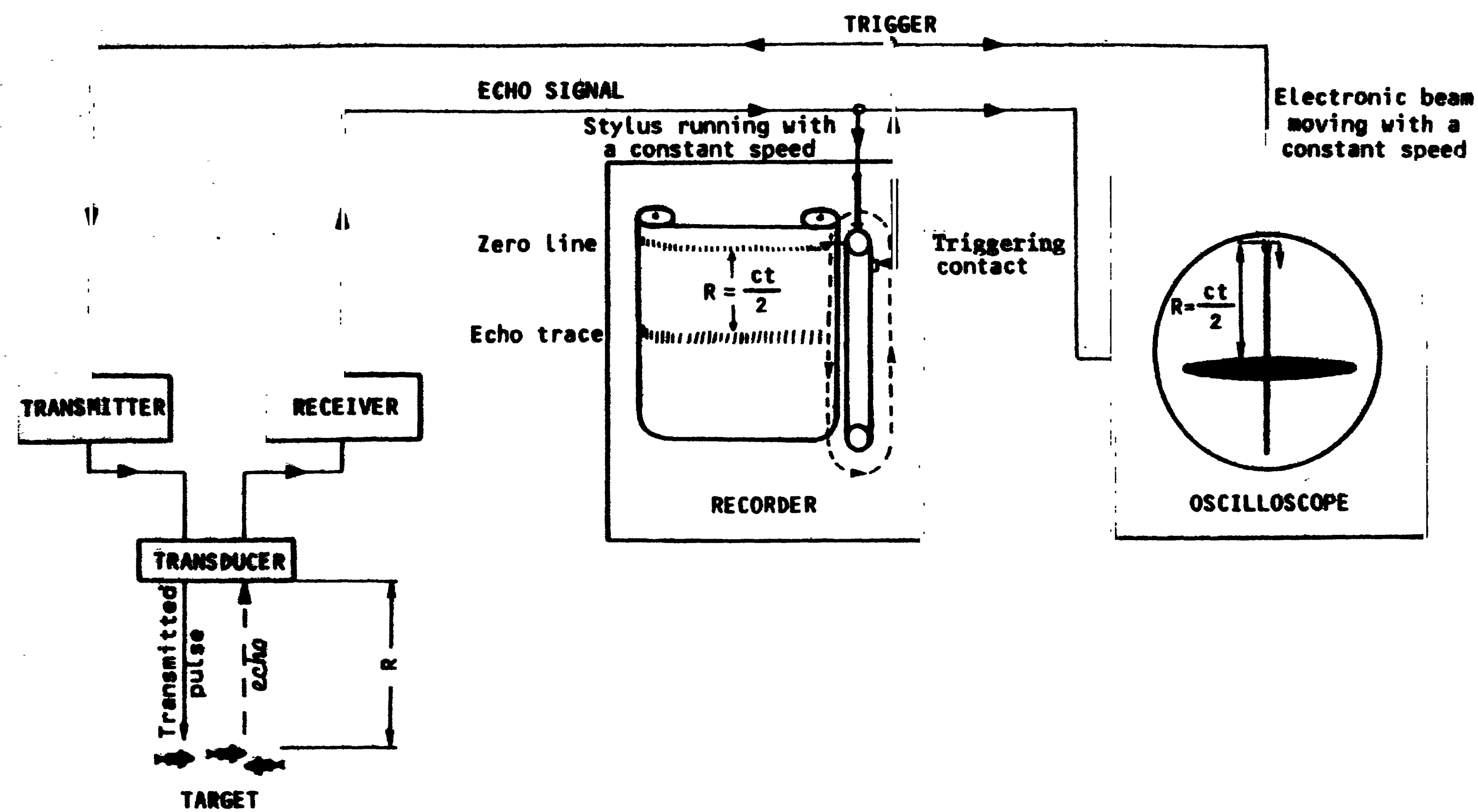


Figure 4 Simplified diagram of an echosounder detecting and locating fish

sophisticated processors and displays have been developed for measuring the quantity of fish detected, particularly echo integrators which are discussed in Chapter 3.

As mentioned above, information about underwater targets is received in coded form as an echo signal; the main function of a processor is to decode the signal to obtain the required items of information. The measurement of various parameters of echo signal in order to infer various properties of the target requires a knowledge of the laws of acoustics, the transmission of sound waves by the transducer, their propagation in seawater, the reflective properties of underwater targets and the conversion of acoustic waves by the transducer into voltages. It is essential that users of sonar systems understand the basic principles of operation of the system in order to make efficient use of the system and intelligent interpretations of the results and thus obtain accurate information on fish stocks, particularly estimates of biomass.

2. ELEMENTARY ACOUSTICS

2.1 Sound Waves

The simplest and best-known kind of sound wave is produced by a vibrating surface, which moves backward and forward in a regular harmonic motion. Let us consider the spreading of sound waves produced by a gong as shown in Figure 5. When we strike a gong it starts vibrating and becomes a source of sound waves. The particles of the medium (i.e. air or water) in contact with the gong are displaced by it and transfer its vibrations to neighbouring particles of the compressible medium. The vibrations of the gong thus cause a disturbance in the medium which spreads through it in a form of sound waves. The sound waves reach the ear of the observer whose eardrum and related parts vibrate, transferring to the brain signals corresponding to the nature of the waves produced by the gong.

The position of the vibrating surface of the gong changes periodically in a regular harmonic motion. During one cycle of vibration the surface of the gong moves from its resting or zero position in one direction, reaches its maximum amplitude, then returns to its zero position, then moves in the opposite direction to its maximum amplitude and from there returns to its zero position again. The whole vibration cycle then starts again (see Figure 6a). The number of cycles completed in unit time is called the frequency of vibration "f" and it is measured in Hertz (Hz), which is the number of cycles per second.

Vibration alternately exerts high and low pressure on particles adjacent to the vibrating surface, and the disturbance radiates in all directions from the source in the form of spherical pressure waves, or sound waves. As a result, pressure at any point in the medium varies periodically with time, and at any given time pressure varies according to the distance from the source, as shown in Figure 6. (Strictly speaking, this description is exact only for a point source of sound, but it also applies to a source of some size, like the gong, at all distances substantially larger than the dimensions of the source).

The speed at which the pressure wave spreads through the medium (i.e. the rate of travel of a pressure maximum or minimum) is the velocity of sound, usually denoted "c", and it depends largely on the density of the medium, not on the frequency or amplitude of the pressure oscillation. (In air the velocity of sound is about 330 m/sec; in seawater about 1500 m/sec).

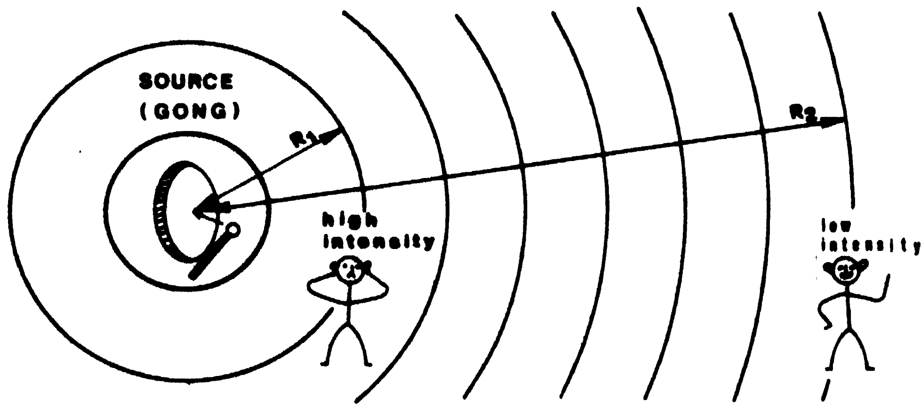


Figure 5 Sound waves generated by a gong

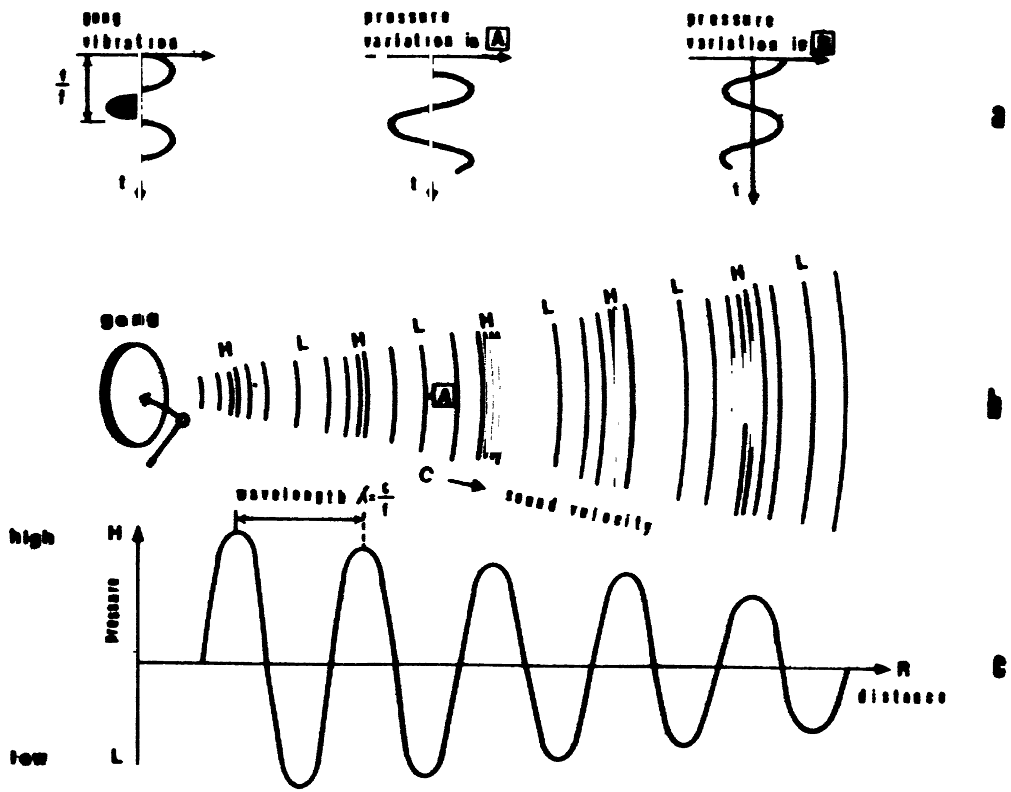


Figure 6 Formation of sound waves
(a) Vibration of source and variation of pressure at differing points in the sound field
(b) Source of sound and pressure waves in an acoustic field
(c) Amplitude of a pressure wave versus distance at an instant of time

The wavelength (λ) of a sound wave (i.e. the distance between successive pressure maxima or minima) is determined by its frequency (f) and the velocity of sound (C) by the simple relationship:

$$\lambda = c/f \qquad (2)$$

2.2 Sound Intensity

The power of a vibrating gong, set in motion by a hammer, depends on the amplitude of its oscillation. The harder the stroke is, the greater is the amplitude of the gong's oscillation and therefore the amplitude of the pressure oscillation and particle motion set up in the medium at the surface of the gong.

When a sound wave passes a point in the medium, the transmitted energy consists of alternatively the kinetic energy of the particles in motion and the potential energy due to pressure differences. It is most convenient to measure this energy as the average amount of energy crossing a unit surface area normal to the direction of propagation in a unit of time. This measure is called the intensity of sound, denoted "I".

In other words the intensity is defined as the average power per unit area, normal to the direction of propagation of sound wave, and it can be expressed as:

$$I = \frac{\overline{(p^2)}}{\upsilon c} = \overline{\frac{\text{power}}{\text{area}}} \ (\text{or } \frac{\text{mean-power}}{\text{area}}) \qquad (3)$$

where $\overline{(p^2)}$ denotes the average value of the squared pressure difference over complete cycle of the pressure oscillation, υ is the density of the medium and c is the sound velocity.

If pressure is measured in pa, density in kg/m^3 and velocity in m/s, the units of sound intensity will be W/m^2 (watts per square metre).

2.3 Propagation of Acoustic Waves

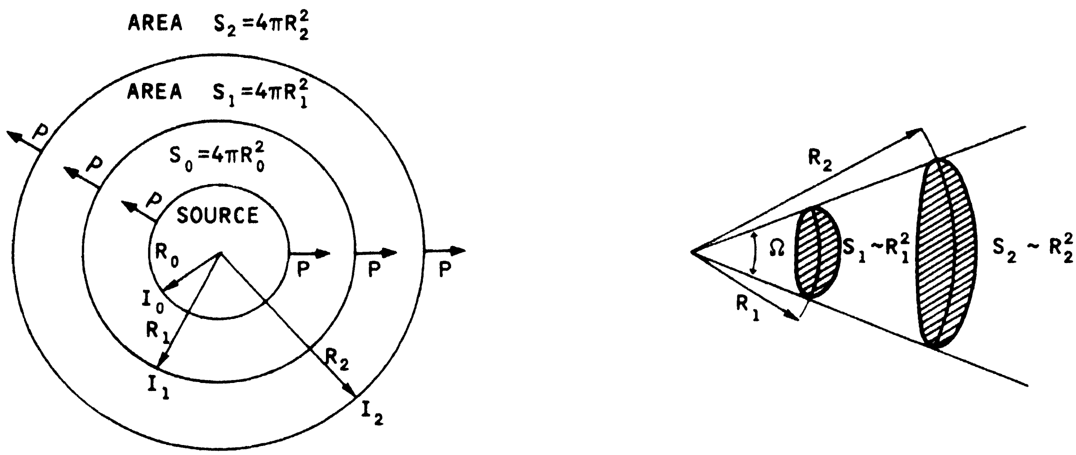
By experience we know that an observer who is near an acoustic source hears a more intense sound than one far from the source. It follows, therefore, that sound intensity must decrease with distance from the source (Figure 5). There are two reasons for this: spreading of the wave in all directions as it radiates from the source, and attenuation by absorption (i.e. loss of energy to friction etc.).

2.3.1 Spreading in an ideal medium

Let us assume that acoustic waves are propagated rom a point source through an ideal medium, i.e. lossless medium. The power generated by the source is radiated in all directions and spherical waves are formed around it (Figure 7a). Since there is no loss in the medium, the power P_R crossing an entire spherical surface must be the same at any distance R from the source, or:

$$I = \frac{\overline{P}}{A} = \frac{\overline{\left(\frac{E}{T}\right)}}{A} = \frac{\overline{(P^2)}}{\upsilon c}$$

where P = power
A = area
I = intensity
E = energy
T = time



$$P_R = I_1\, 4\pi R_1^2 = I_2\, 4\pi R_2^2 = \cdots = \text{const}$$

$$P_R \sim I_1 R_1^2 = I_2 R_2^2 = \cdots$$

a b

Figure 7 Spherical acoustic waves radiated by a point source of sound (a) non-directional radiating (b) directional radiating

$$P_R = I_R S_R = \text{constant}$$

where I_R = sound intensity in a given direction from the source at a distance R

$S_R = 4\pi R^2$ = surface area of a sphere of radius R equal to the distance from the source

The relationship between the intensities of the sound waves at distances R_1 and R_2 from the source is given by:

$$I_1 \, 4\pi R_1^2 = I_2 \, 4\pi R_2^2 \tag{4}$$

Let us define the intensity of the source as the acoustic intensity measured at the standard distance from the source $R_0 = 1$ m. The relationship between source intensity and the intensity of sound at distance R from the source will then be:

$$I_0 \, 4\pi 1^2 = I_R \, 4\pi R^2 \tag{5}$$

where I_0 = intensity of sound radiated by source

I_R = intensity of sound at distance R from the source

By transformation of equation (5) we can find that, in an ideal medium, the intensity of a sound wave at a distance R from the source is inversely proportional to the square of distance (R^2) and directly proportional to the radiated intensity (I_0):

$$I_R = \frac{I_0}{R^2} \tag{6}$$

Thus if a point source generates sound waves with a constant power in an ideal medium, the sound intensity decreases with the square of distance because of geometrical spreading of the spherical waves.

If the source generates acoustic waves directionally, i.e. within a given solid angle Ω (Figure 7b), the intensity of the sound wave in the ideal medium decreases with the distance according to the same law, because the surface areas of the section of the sphere within the solid angle Ω increases in proportion to the square of the distance: $S = \Omega R^2$ or $S \sim R^2$. (The concept of a solid angle is explained in Appendix I).

2.3.2 Propagation in a real medium

In any real physical medium, e.g. seawater or air, we can expect a loss of power from transmitted acoustic waves. In other words, the sound wave is attenuated in a real medium owing to friction between particles, absorption of power and scattering. The effect of attenuation alone is an exponential decrease of sound intensity with distance from the source, or a multiplier of the form $\exp(-\beta R)$, with a coefficient β whose value depends on the acoustic properties of the medium and the acoustic wavelength.

The two types of losses are thus:

(a) Geometrical spreading: sound intensity decreases with the inverse square of distance, i.e.

$$\frac{1}{R^2}$$

(b) Attenuation: sound intensity decreases exponentially with distance, i.e.

$$\frac{1}{\exp(\beta R)}$$

The resulting intensity at a distance R is:

$$I_R = \frac{I_0}{R^2 \exp(\beta R)} \qquad (7)$$

The logarithmic decrement of attenuation (β) depends on the density of the medium and the wave length or frequency of the propagated sound wave. Sound waves of high frequency are attenuated more than those of low frequency. The values of the logarithmic decrement of attenuation for seawater are given in Figure 8.1/

2.4 Properties of Transducers

Generally speaking, a transducer is a device that converts one form of energy to another. Specifically, in sonar systems, a transducer converts electrical energy into sound energy and vice versa. In sonar systems applied in fisheries a transducer functions as follows:

(a) In the "transmitting mode" it converts the energy of oscillation of the electrical network of a transducer into mechanical vibrations of the transducer's surface, which in turn produce sound waves in the surrounding water.

(b) In the "receiving mode" it converts the vibration of its surface, generated by the received echoes, into voltage oscillation at the electrical terminals of the transducer.

In both modes the following relationships exist between the parameters of the sound wave and the voltage at the transducer's terminals:

- the pressure of the sound wave is proportional to the voltage

- since the intensity of the sound wave is proportional to the squared pressure, it will also be proportional to the squared voltage:

$$I \sim u^2 \qquad (8)$$

2.4.1 Directivity pattern

In using sonar systems for the detection and location of fish, it is necessary to insonify a known volume of water, i.e. to generate sound waves that are transmitted and received within a well-defined beam (Figures 1 and 9). The effect of directing sound within a beam is similar to that of a searchlight: only the target (group of fish) insonified by the transmitted beam width will be detected and recorded.

1/ When sound intensity is measured in decibel units, attenuation is represented by a coefficient denoted α. Since decibel units are based on common (i.e. decimal) rather than natural logarithms, α and β are not equal but are strictly proportional: $\alpha = 4.3\ \beta$. (See Appendix II).

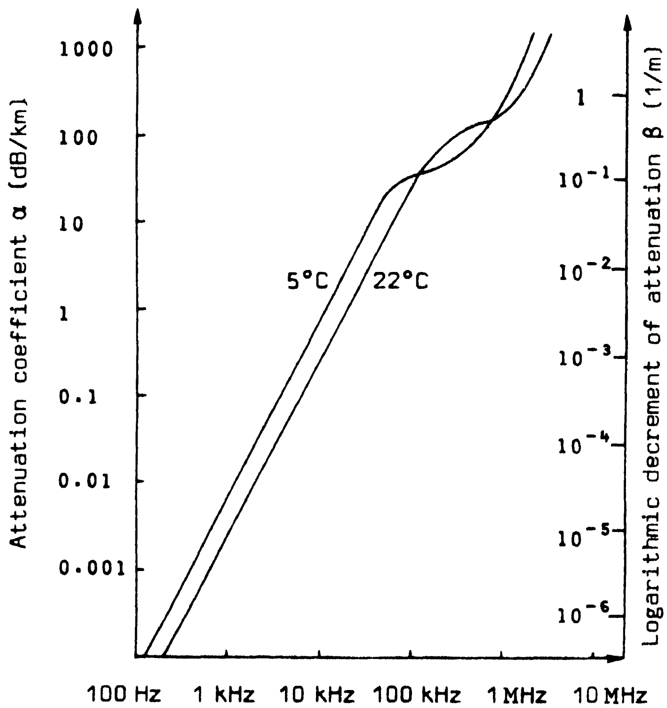


Figure 8 Logarithmic decrement of attenuation β and coefficient of attenuation α versus frequency of transmission for sea water at 5° and 22° temperature (reproduction from Forbes and Nakken, 1972)

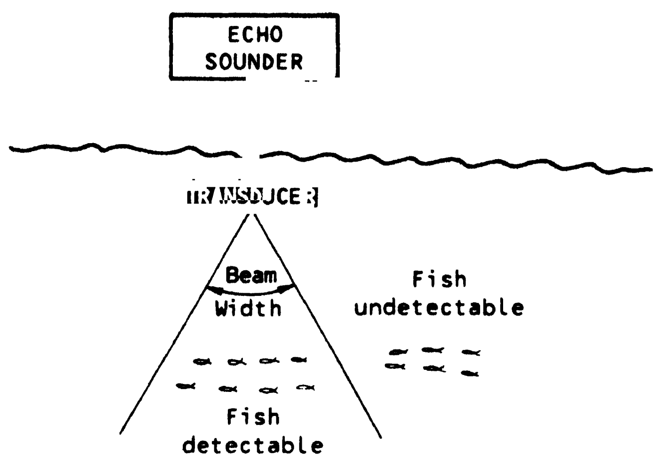


Figure 9 Detection and location of fish by a directional transducer of an echosounder

A point source radiates sound uniformly in all directions. If two point sources located fairly close to one another both generate the same sound, however, the resulting sound intensity will not be the same in all directions. In some directions the waves from the two sources will be in phase or nearly so, and will reinforce each other to produce a high intensity; in some other directions they will cancel each other. This phenomenon, called interference, produces a regular but very non-uniform distribution of sound intensity according to direction. (A detailed description is given in Appendix III).

A transducer can be regarded as an array of point sources of sound. The resulting distribution of intensity has a maximum on the axis of the transducer (a line passing through its centre perpendicular to the surface) and lower values elsewhere, so it is convenient to describe the intensity distribution, or directivity pattern, of a transducer as the relative intensity at each bearing (ϕ,θ) (see Figure 10a) with respect to intensity along the axis, $I(0,0) = I_m$. This relative value is denoted $b(\phi,\theta)$. Thus:

$$b(\phi,\theta) = \frac{I(\phi,\theta)}{I(0,0)} \tag{9}$$

(The two intensities can be measured at any range; their ratio is constant).

Figure 10b shows the directivity pattern of a circular transducer. Intensity is highest along the axis. With increasing deviation from the axis, intensity first decreases to a minimum, then increases again to a value much lower than the maximum on the axis, then decreases and so on. The region of high values near the axis is called the main lobe of the beam, and the successively smaller peaks around the main lobe are called side lobes. (Commercial transducers are often rectangular. Their directivity patterns are more complicated but still have a dominant main lobe and smaller side lobes, although these are not "circular", i.e. they are different in axis X-Z and Y-Z).

Just as a transducer in the transmitting mode can be regarded as an array of point sources of sound, a transducer in the receiving mode can be regarded as an array of point receivers of sound. Considered in this way, it is clear that the transducer's directivity pattern applies in both modes. Thus the intensity of the echo from a target at a bearing where the directivity function is, say, $b(\phi,\theta) = 0.5$, will be $(0.5)^2$ or only one quarter as great as the intensity of the echo from an identical target at the same range on the axis of the transducer.

Because of the directivity patterns of transducers, it is not a simple matter to define the volume of water insonified by the beam so as to be able to interpret echoes correctly. The receiver of a sonar system provides no information on the bearing of a target, so an observer cannot tell whether an echo of moderate strength represents a small target on the axis of the transducer or a large target at the same range to the side of the axis.

Rather than trying to deal with directivity from the start, it will be convenient here to define an ideal transducer with a uniform directivity pattern and a simple conical beam. This concept will make it much easier to develop the basic principles of acoustic estimation of biomass, and at a later stage the effect of directivity will be considered again.

Figure 11 shows an ideal transducer, which is defined by the following properties:

(a) In the transmitting mode, the intensity of the radiated sound wave is constant (I_m) at any given range within the whole beam width of angle ψ, and 0 (zero) at all angles exceeding the beam angle ψ.

(b) In the receiving mode, the response to a sound wave received from a source radiating with a constant power from a given range, is constant for all locations of the source within a beam width of angle ψ, and 0 (zero) for all locations outside it.

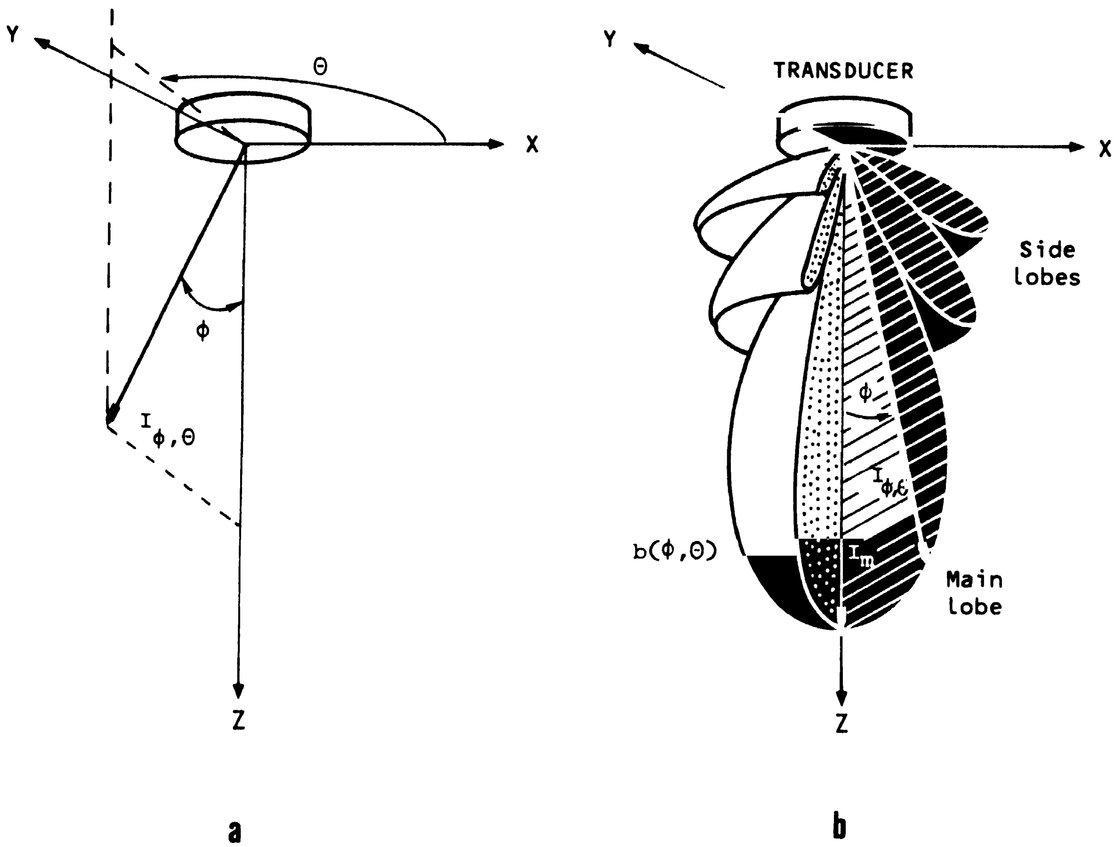


Figure 10 Three-dimensional view of the directivity pattern of a circular transducer
(a) coordinates
(b) directivity pattern

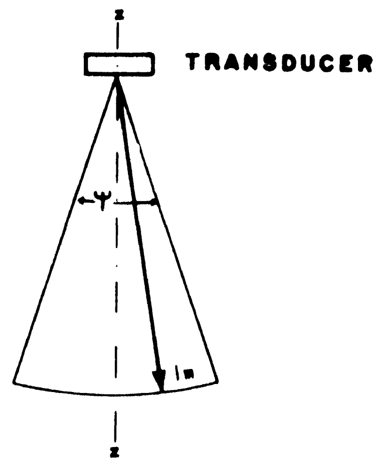


Figure 11 Ideal beam pattern of a transducer

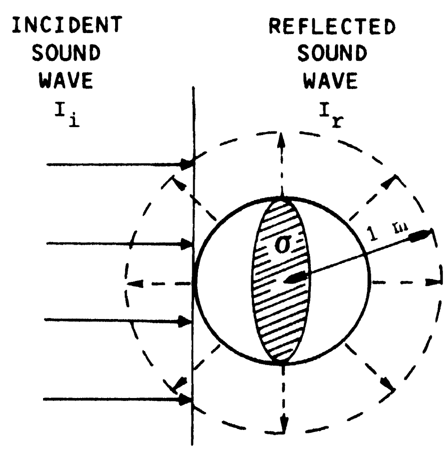


Figure 12 Reflection of sound waves by a sphere

2.4.2 Transducer bandwidth

The transducer of a pulsed sonar system usually functions for both transmission and reception. It is designed to be most efficient over a limited band of frequencies, the centre of which is the resonant frequency, often quoted as the operating frequency of the sonar. The edges of this frequency band cannot be infinitely steep so the band limits are referred to the points where the response is 0.707 of the maximum, or -3dB.

This is achieved in a practical system when the bandwidth in Hz equals the reciprocal of the pulse duration in seconds, e.g. a 1ms pulse requires a bandwidth of 1 kHz. To preserve the amplitude and shape of the pulse the bandwidth must not be less than this, nor must it be significantly greater. This is because noise exists at all frequencies so the wider the band the more noise will enter the system.

2.5 Reflection by a Single Target

When a sound wave transmitted by a transducer and propagated through a medium meets an object of a density different from that of the medium itself (e.g. a fish in seawater), part of its acoustic energy is absorbed by the target and the remaining part is reflected.

Each target (i.e. reflecting object) has characteristic reflective properties which can be expressed by the ratio between intensities of incident and reflected sound wave:

$$ts = \frac{I_r}{I_i} \qquad (10)$$

where I_r = intensity of reflected sound waves at 1 m from the target

I_i = intensity of incident sound waves at 1 m from the target

The reflective properties of the target can also be measured by another parameter, the effectuve scattering area of the target or the "equivalent cross-section". In order to explain the meaning of this parameter we will introduce the concept of the ideal target. Let us imagine an ideal totally reflecting sphere (e.g. a perfectly spherical air bubble water). Such a target does not absorb power, and 100% of the incident sound wave upon it is reflected (Figure 12). The directivity pattern of this target is uniform. In other words, the acoustic centre of the target, i.e. the centre of the sphere, can be considered as the source of reflected spherical sound waves. According to Section 2.2 the amount of power incident on the target is equal to the intensity of the incident sound wave "I_i" times the area of the target's cross-section normal to the direction of propagation "σ". According to Section 2.3.1 the amount of power reflected at the standard distance from the acoustic centre of the sphere R_0 = 1 m is equal to the intensity of the reflected sound wave "I_r" times the surface area of the sphere ($4\pi R_0^2$). Due to the total reflection, the total incident and reflected powers are equal:

$$I_i \sigma = I_r 4\pi 1^2$$

Therefore, we can define the equivalent cross-section of the target as:

$$\sigma = 4\pi \frac{I_r}{I_i} \qquad (11)$$

For a totally and uniformly reflecting target, the equivalent cross-section is equal to the area of the target normal to the incident sound wave

($\sigma = \frac{\pi D^2}{4}$ where "D" is the diameter of the sphere)

But for any target we can calculate a value of σ, i.e. the cross-section of an ideal target that would reflect sound of equal intensity at an equal distance from its acoustic centre. In other words, any given target can be substituted by an ideal one of equivalent cross-section σ.1/

The equivalent cross-section of a target depends on the dimension of the target relative to the wave length, and on the density of the target relative to the density of the medium. The greater is the difference between the densitites of water and target, the more energy will be reflected.2/

For objects with a large radius of curvature compared to wave length, the echo is originated by back reflection, while for the objects with a radius of curvature smaller than the wave length, the echo is formed by back scattering of the incident sound wave. The above terminology is in use due to the different mechanisms of reflection and scattering, and a detailed description including Huygen's theory of waves is beyond the scope of this manual; however, the effect is the same in both cases and any insonified object can be considered as the source of a returned sound wave whose intensity is determined by the target's acoustic parameter, i.e. (σ) or (ts).

Fish sizes are of the same order of magnitude as the wave length usually applied in sonar systems. A fish is not a homogeneous sphere and the returned sound wave can be considered as a contribution of back scatterings by different parts of the fish body. The intensity of the returned sound wave therefore varies according to direction, which in effect gives a reflecting directivity pattern similar to that of a transducer (see Section 2.4.1). But for any target we can measure at any given direction the ratio of intensities between the reflected and the incident sound wave, and then calculate its equivalent cross-section (σ), (formula 11).

The intensity ratio (ts), or the equivalent cross-section (σ), is the acoustic parameter of the target.3/ It depends <u>only on the acoustic properties of the target</u> and it expresses quantitatively the relative sound intensity that is reflected.

Finally we can rewrite equation (11), and in order to simplify the notation, let us use the sign "proportional" ($\sim$) instead of "equal" (=), and omit the constant value ($\frac{1}{4\pi}$). The intensity of the reflected sound will then be:

$$I_r \sim I_i \sigma \tag{12}$$

Thus the intensity of the sound wave reflected by a single target is proportional to the intensity of the incident sound wave and to the scattering cross-section of the target (Figure 13).

1/ Another term for equivalent cross-section is scattering cross-section.

2/ The reflection index is given as $\mu = \frac{c_1\nu_1 - c_2\nu_2}{c_1\nu_1 + c_2\nu_2}$, where:

c - sound velocity, ν- density, 1 indicates water, and 2 indicates target (Forbes and Nakken, 1972).

3/ In decibel units the parameter of the target is called the <u>target strength</u> (TS):

$$TS = 10 \log \frac{I_r}{I_i} = 10 \log \frac{\sigma}{4\pi}$$

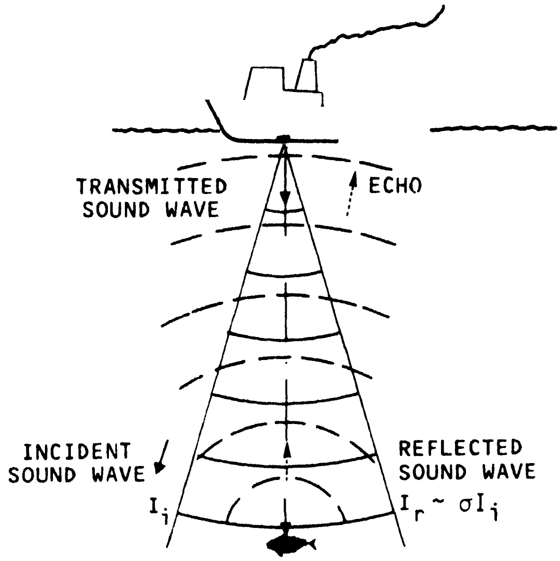


Figure 13 Reflection of sound waves by a single target

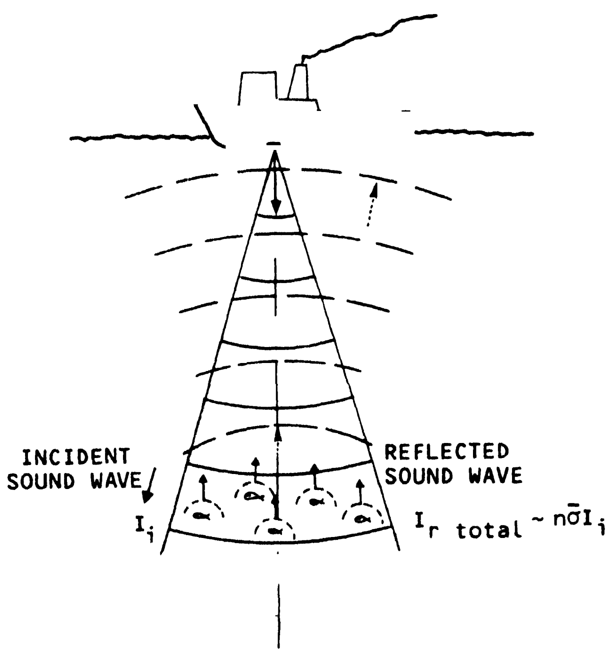


Figure 14 Reflection of sound waves by a multiple target

2.6 Reflection by a Multiple Target

A group of single targets (fish that occupy a certain volume of water insonified instantaneously by a transmitted sound wave can be treated as a multiple target (Figure 14). Each individual target becomes the source of a reflected sound wave,1/ and the acoustic centre of the multiple target can be considered as the source of a composite reflected wave. If the individual targets are randomly distributed, the total power reflected by the group will, on average, be the sum of the power reflected by the individuals.

Hence, the total intensity of the sound wave reflected by a multiple target is the sum of the intensities reflected by the individual targets:

$$I_{r\ total} = I_{r1} + I_{r2} + \ldots + I_{rn}$$

where I_{rj} = the intensity of the sound wave reflected by the j^{th} individual target

n = number of targets

For a group of n targets of similar acoustic properties, we can estimate the average value of the intensity of the sound wave reflected by an individual target $\bar{I}_r$. Hence the total intensity of the reflected wave will be:

$$I_{r\ total} = n\,\bar{I}_r \tag{13}$$

where,

$$\bar{I}_r = \frac{1}{n}\sum_{1}^{n} I_{rj} = \text{average intensity of sound reflected for a single target}$$

The average equivalent cross-section per target ($\bar{\sigma} = \frac{1}{n}\sum_{1}^{n}\sigma_j$), according to the definition (formula 11), will be:

$$\bar{\sigma} = 4\pi\,\frac{\bar{I}_r}{I_i} \tag{14}$$

By substituting $I_r = \frac{\bar{\sigma}}{4\pi}$ (derived) from equation (14) into equation (13) we get:

$$I_{r\ total} = \frac{n\bar{\sigma}}{4\pi}\,I_i \tag{15}$$

Thus the total intensity of the sound wave reflected by a multiple target is proportional to the number of individual targets (n), the average scattering cross-section per target ($\bar{\sigma}$), and the intensity of the incident wave (I_i).

The above formula can be written in a simplified notation as follows:

$$I_{r\ total} \sim n\,\bar{\sigma}\,I_i \tag{16}$$

1/ The term "reflected sound wave" will be used hereafter for simplicity to cover reradiated and back scattered waves as well.

This model of reflection by a multiple target is valid under the assumption that the medium is homogeneous and that secondary reflection between individual targets is negligible.1/

Equation (16) is the basis for quantitative acoustic estimates of fish biomass. It has been proved by experiments to be valid for scattering aggregations of fish and for schools of medium densities.

The model should be applied with caution in the case of very dense schools because of the following effects can occur:

(a) Non-homogeneous medium: The medium in the volume occupied by a very dense school can be treated as a mixture of seawater and fish bodies, while the medium beyond this volume consists of seawater only. One can expect the attenuation of sound in the volume occupied by fish to be higher than the attenuation in seawater, because of additional absorption of sound energy by fish bodies. Also, refraction of sound can occur at the boundary of the two media (see Section 2.7).

(b) Secondary reflection: In very dense schools the distances between individual fish are small and one can expect secondary reflection.

2.7 Refraction and Deflection of Sound in the Sea

Seawater is not a homogeneous medium. It usually consists of a number of layers of different densities caused by variation of temperature and salinity with depth. It is a general principle in physics that waves crossing a density boundary will be turned or refracted, unless they cross it perpendicularly. The amount of refraction depends on the crossing angle and the difference between the velocities of wave propagation in the two layers. Particularly in sonar work, but also sometimes in echosounding, the transmitted and reflected sound waves cross boundaries obliquely, and when this occurs it must be taken into account.

The velocity of sound in seawater is a function of temperature and salinity.2/ According to the empirical formula of Kuwahara (Urick, 1967) the velocity of sound in seawater can be expressed as follows:

$$c = 1445 + 4.66\,t - 0.055\,t^2 + 1.3\,(s-35) \qquad (17)$$

where c = sound velocity (m/s)

t = temperature (^{o}C)

s = salinity (‰)

1/ Secondary reflection: each target reflects the "original" sound wave generated by a source. The sound wave reflected by a single target insonifies a neighbouring target which reflects it back; this is called secondary reflection. If the distance between targets is large enough, secondary reflection is negligible.

2/ The influence of depth on sound wave velocity is negligible in fisheries work, which is almost always carried out in the upper layers of the water column.

Let us assume that a sound wave is propagated horizontally through seawater in which because of the temperature and salinity structure, sound velocity varies with depth (Figure 15). If sound velocity decreases with depth, the upper part of the wave front will travel faster than the lower part, so the wave will turn downward, i.e. toward the region where the velocity of sound is lower (Figure 15a). If the velocity of sound increases with depth, the wave will turn in the opposite direction (Figure 15b).

If the variation of sound velocity with depth is known, it is possible to determine the path of waves graphically by applying the geometrical theory of acoustic rays. (As in geometric optics, the concept of an acoustic ray is a useful device for describing the refraction of a wave). The most important result of ray theory for present purposes is Snell's law 1/: when a ray crosses a boundary between different sound velocities, the ratio of the cosine of the crossing angle and the velocity of sound remains constant (Figure 16):

$$\frac{\cos \theta_1}{c_1} = \frac{\cos \theta_2}{c_2} = \frac{\cos \theta_3}{c_3} = \ldots = \text{constant} \tag{18}$$

Figure 17 shows an example of how to predict the path of a sonar beam graphically by application of Snell's law. The sound velocity in each layer can be calculated from formula (17) by inserting the values of temperature and salinity measured by bathythermograph and salinometer.2/

In the example presented in Figure 17a, the velocity of sound is constant with depth. The sonar transducer is fixed at a given depth R, and it transmits horizontally within the beam angle (ψ). The lower ray, which represents one boundary of the transducer's beam does not change direction, while the upper one is reflected downwards by the surface at the same angle.

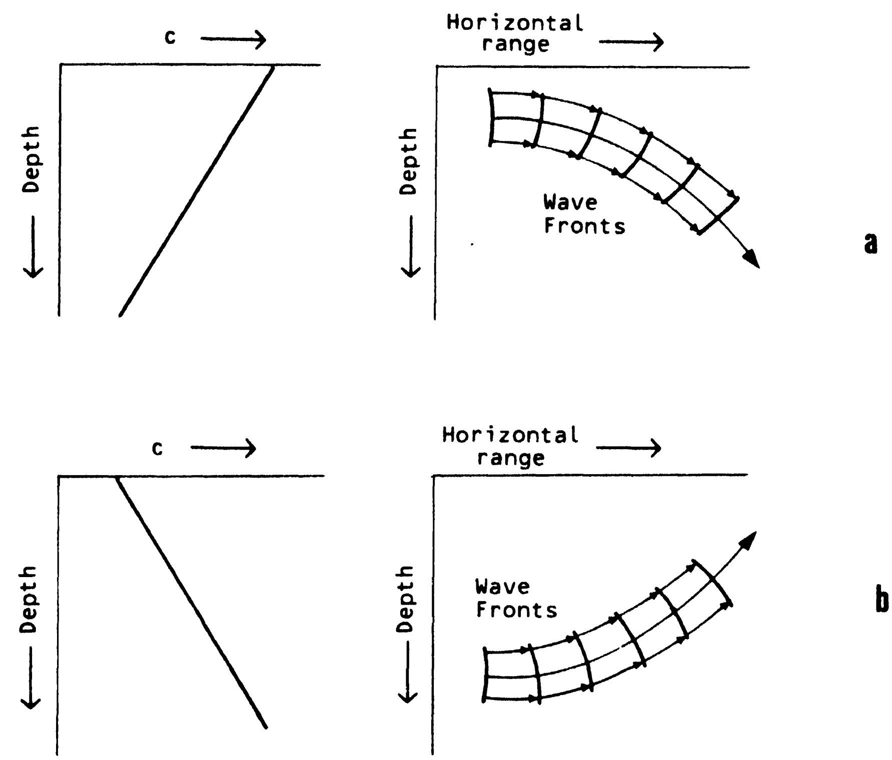
In the example of Figure 17b the velocity of sound varies with depth.3/ We can distinguish three layers of the average sound velocity (c_1, c_2, c_3) and plot the ray's path according to Snell's law. The straight lines in Figure 17b show the path of the beam calculated according to the discrete approximation of the sound velocity profile. However, since the sound velocity in fact varies continuously with depth, the actual path of the beam will follow the curved lines shown in the figure, rather than the straight line approximations.

Usually, layers of water of different temperature and salinity are formed in the ocean horizontally, i.e. stratification occurs vertically and the boundaries between layers are for the most part horizontal or nearly so. When using an echosounder (Figure 1a), the sound beam is directed almost vertically. The sonic rays cross the layers of different water density almost perpendicularly and the deflection of the sound beam can usually be considered to be negligible. The beam of sonar however, is

1/ A detailed presentation of acoustic rays theory and its application in hydroacoustics is given by Urick (1975) and by Clay and Medwin (1977).

2/ This method of reckoning the path of a sonar beam graphically is a simplified one, which can be easily applied on board fisheries vessels. More precise calculation can be done by computer.

3/ The sound velocity profile shown in Figure 17b is typical of tropical waters. The upper layer of water is warmer than the lower one, and we can distinguish the thermocline.



<u>Figure 15</u> Refraction of sound (reproduction from Forbes and Nakken, 1972)
(a) velocity decreasing with depth
(b) velocity increasing with depth

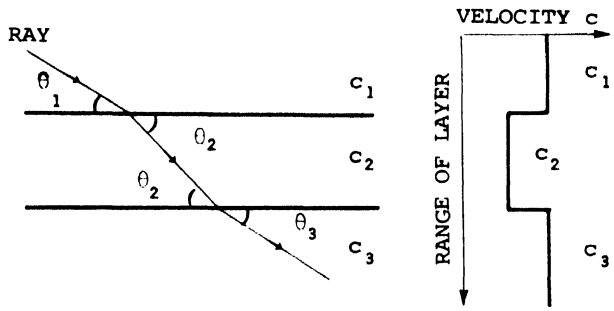


Figure 16 Refraction of sound in a layered medium

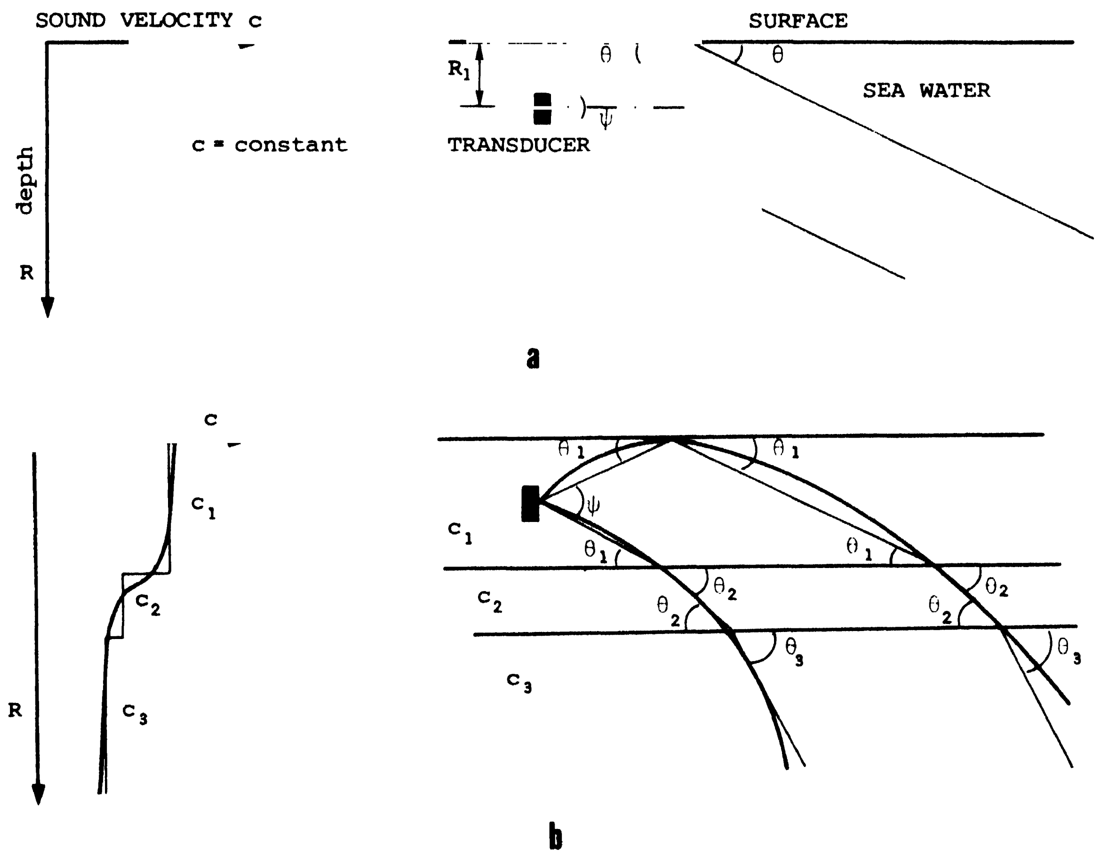


Figure 17 Graphical reckoning of the path of a sonar beam
(a) constant sound velocity
(b) sound velocity varying with depth

directed almost horizontally (Figure 1b and 17). The sonic rays cross the layers of different water density at fairly large angles, which cause large deflections of the sound beam. In these cases, reckoning of the sonar's beam path is very important for determing and adjusting the detection range of the sonar.1/

2.8 Reverberation

Seawater is not a pure liquid; it contains a number of small particles ranging from tiny particles of dust and sand to small organisms of phytoplankton and zooplankton. After stormy weather the water near the surface contains a large quantity of small air bubbles.

These small particles intercept and re-radiate a part of transmitted acoustic power. The radiation of sound by these small particles is called "scattering". The total effect of scattering, i.e. the sum of scattering in the volume of water insonified by a transducer's beam, is called "reverberation". Reverberation is very well known to those who operated a sonar for fish detection. It is heard as a long decaying tone or shuffling sound (depending on the reverberation conditions) following the transmitted pulse. Reverberation can be treated as a part of the background noise in a sonar system.

2.9 Noise

Besides the echo signals from underwater targets, the receiver of a sonar system is subject to noise. The noise masks the echo signals and this interferes with the detection of underwater objects. The higher the noise level relative to the echo signal, the more difficult it is to detect underwater objects.

The noise observed on the display of a sonar system is a combination of ambient noise, reverberation and self-noise of the equipment. Generally speaking, the ambient noise consists of natural sea sounds generated by sea waves, aquatic animals, etc.

The self-noise is caused by the equipment itself, the machinery of the vessel and her movements. (The electronic self-noise of the equipment is negligible). The main source of self-noise which affects the performance of a sonar system are:

(a) noise generated by the propeller of the vessel and vibrating machinery

(b) flow noise, i.e. a hydrodynamic noise generated by the flow of water around the transducer's face or dome and the vessel's hull.

When the propeller rotates fast in the water, regions of low or negative pressure appear at the tips and surfaces of the propeller's blades. If the negative pressure is high enough, the water is ruptured and cavities in a form of short-lived bubbles appear. These bubbles collapse, producing a series of sharp pulses of sound which causes a wide frequency noise. This phenomenon is called cavitation. The resulting noise can be reduced during steaming either by reducing the revolutions of the propeller or by adjusting the propeller's pitch angle. It can also happen that the propeller is not designed properly and in this case modifying the edges or tips of the blades is the only way to reduce the noise.

1/ For example, one can easily observe that in order to increase the sonar range in Figure 17b, the transducer should be tilted upward.

It is evident that the self-noise level increases with the speed of the vessel. With increase of the vessel's speed, the machinery goes faster, the propeller rotates faster and the flow of water around the transducer is faster. On the other hand, the self-noise level also depends on the state of the sea. It will be low when the sea is calm and the vessel moves smoothly. When the sea is rough the vessel pitches and rolls, and the movements of both the hull and the propeller are affected by strong waves, which cause an increase in the self-noise level.

When using a sonar system for quantitative fish surveys, the self-noise level has to be measured in order to estimate the minimum detectable echo signals. Generally speaking, when the noise level appears too high for a given minimum detectable echo signal, speed of the vessel should be reduced in order to reduce the noise level.

2.10 Acoustic Properties of Fish

Research on the acoustic properties of fish has been carried out by a number of scientific workers from the earliest days of applying acoustic techniques to fish biomass estimates (Hashimoto and Maniva, 1956; Haslett, 1962, 1970, 1977; Midttun and Nakken, 1971; Nakken and Olsen, 1977; Yudanov et al., 1966; Love, 1970; and others). A wealth of data has been collected covering experiments on measurements of target strength (or equivalent cross-section) of both real fish and artificial models of fish.

Experiments with fish species with swim bladders have shown that the major part of the sound energy is reflected by the swim bladder. Species lacking swim bladders reflect less acoustic energy than those with swim bladders. In general, the reflecting directivity pattern, and the relationship between fish size and scattering cross-section, can be determined for species in both categories.

The acoustic properties of fish as they affect estimates can be summarized as follows:

1) The target strength (or scattering cross-section) of a fish has a directivity pattern quite similar to that of a transducer: the relative intensity of sound reflected by a fish back to the source depends on the "aspect" of the fish, i.e. its orientation relative to the source (see Figs.18 and 26). The directivity pattern depends in general on the anatomy of the fish, its overall size, and the dimensions of the swim bladder relative to the wave length.1/

2) For a given species of fish (i.e. fish of a certain anatomy) and for a given wavelength (or frequency of sound) there is a close relationship between the target strength (or equivalent cross-section) and the size of the fish: the larger the fish, the larger is its target strength or equivalent cross-section.

Figure 18 portrays the reflecting directivity pattern of a cod 69 cm long, at two frequencies, f = 97 kHz and f = 30 kHz, measured by Haslett (1977). The maximum of the acoustic energy reflected by a fish is originated from its dorsal and ventral aspects, i.e. the maximum value of target strength (or equivalent cross-section) is obtained when the fish is insonified to its head-tail axis either from the dorsal or from the ventral side. Also, the directivity pattern of a fish is more complicated (i.e. has a greater number of maxima and minima according to aspect) at a high frequency of sound than at a low frequency

1/ Readers interested in the details of the reflection of sound in relation to the size and shape of the insonified target and wave length, should consult Forbes and Nakken (1972), Urick (1975) and Haslett (1970).

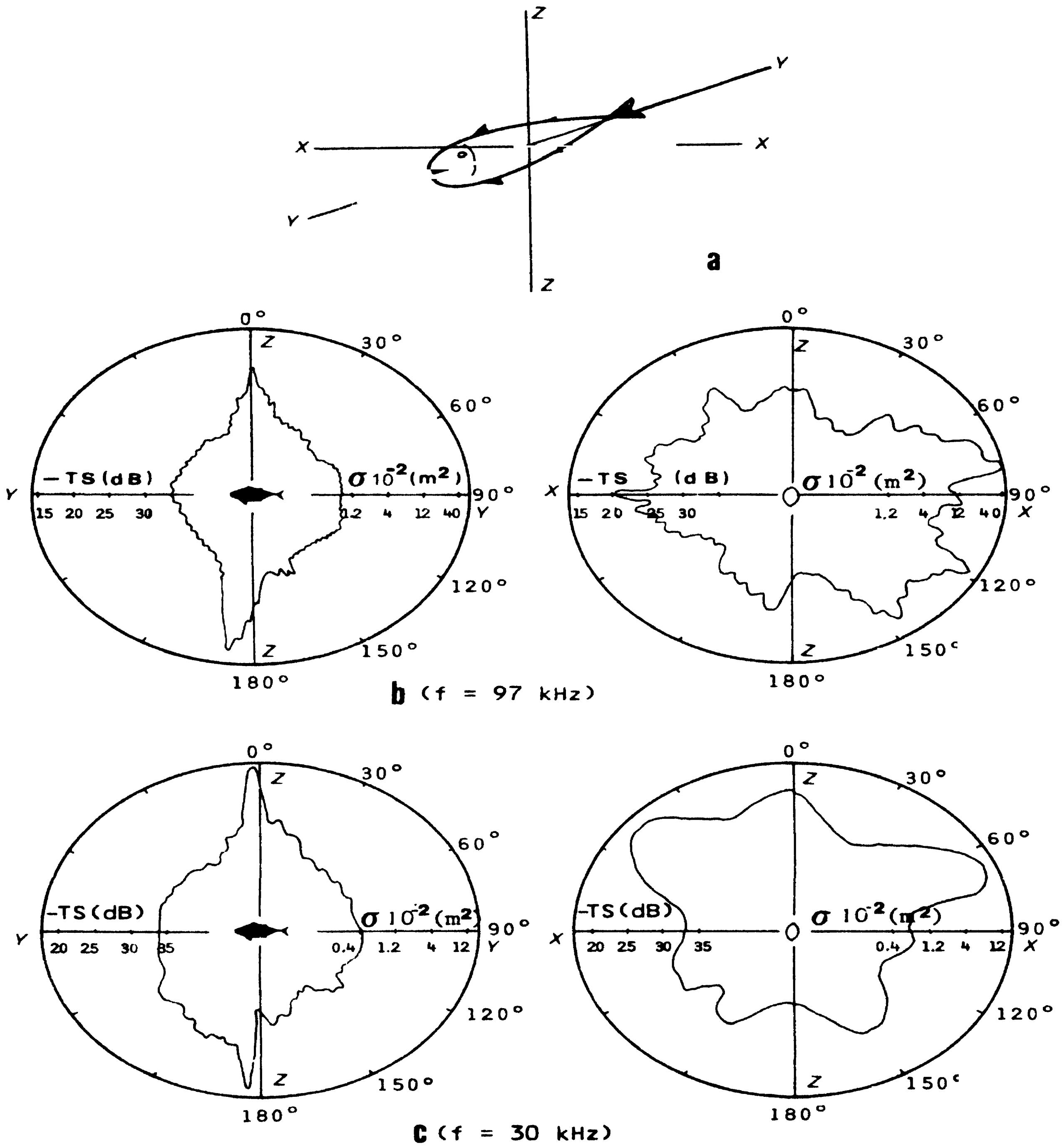


Figure 18 Two-plane polar diagram of the target strength (equivalent cross-section) of fish versus direction of propagation of sound wave for cod of length L = 69 cm

(a) coordinates

(b) diagrams for frequency f = 97 kHz

(c) diagrams for frequency f = 30 kHz

(diagrams constructed according to measurements by Haslett, 1977)

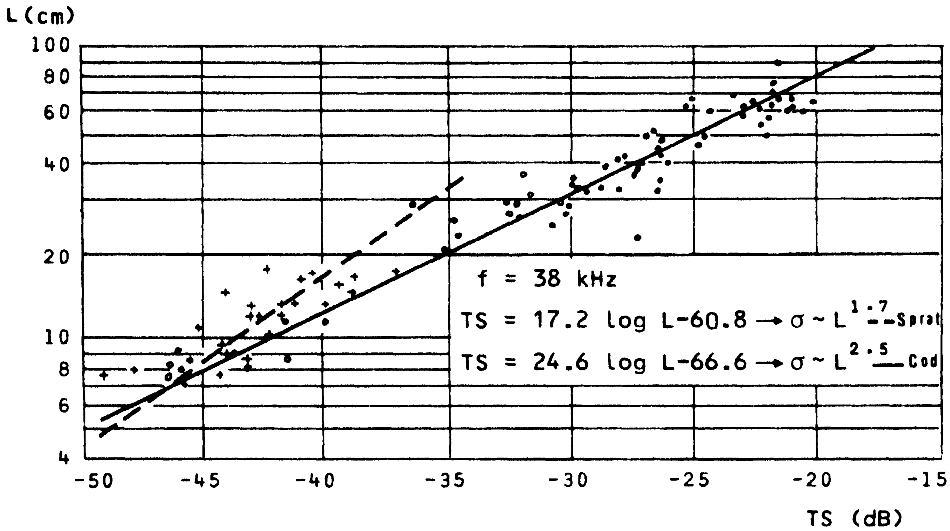


Figure 19 Relationship of the maximum dorsal aspect target strength (equivalent cross-section) and fish length, measured for cod and sprat at frequency f = 38 kHz (Nakken and Olsen, 1977)

Figure 19 shows the observed relationship between the maximum value of the target strength in the dorsal aspect, and fish length, for two species, (cod and sprat) measured by Nakken and Olsen (1977), at a frequency of f = 38 kHz. The linear regression line was fitted to the empirical data. The estimated regression equations of target strength (TS), scattering cross-section (σ) and fish length (L) are:

For sprat: $TS = 17.2 \log L - 60.8;$ $\sigma \sim L^{1.7}$
For cod: $TS = 24.6 \log L - 66.6;$ $\sigma \sim L^{2.6}$

Similar measurements and estimates were done for a number of fish species by a number of researchers. The findings obtained can be summarized as follows:

1. The equivalent cross-section is a linear function of the square of fish length: $\sigma \sim L^2$. (This relationship has been obtained by Love (1971); it expresses a general average for various species although the relationship varies among species from $\sigma \sim L^{1.5}$ to $\sigma \sim L^{2.8}$).

2. For most commercially important species the weight per fish is roughly proportional to the cube of the fish length: $w \sim L^3$.

3. The equivalent cross-section of a fish is therefore proportional on average to its weight to the power $^2/3$ ($\sigma \sim w^{0.67}$); however, this relationship can vary among different species from $\sigma \sim w^{0.5}$ to $\sigma \sim w^1$.

In the absence of a large variation in the size of fish of a given species, we can approximate the relationship with a simple proportionality between the equivalent cross-section and weight per fish:

$$\sigma \sim w \qquad (19)$$

3. HOW TO OBTAIN QUANTITATIVE INFORMATION ON FISH BY ECHOSOUNDING

In Section 2, we discussed the properties and parameters of sound waves, the laws of their propagation in seawater, the reflection of sound by targets, and the properties of transducers.

In this section we discuss how and what kind of information we obtain at the output of a sonar system sounding vertically, i.e. an echosounder. In other words, we explain how to process the echo signal in order to obtain the required information about the targets (specifically fish) appearing in the beam of the echosounder's transducer.

In fish biomass estimates, we are interested primarily in measuring fish quantity or fish density, so we should process the echo signal in a way that provides quantitative information about fish appearing in the column of water sampled by the transducer's beam.

The parameters of the echo signal received at the terminals of the transducer depend on its receiving properties and on the parameters of the received sound wave (echo). Furthermore, the parameters of an echo depend on the parameters of the transmitted sound wave, its propagation in the seawater, and the acoustic properties of the targets. The parameters of the transmitted sound waves depend on the parameters of the transmitted electric signals and the transmitting properties of the transducer.

To be able to process an echo signal according to our requirements we must identify those of its parameters which contain the required items of information on fish quantity or density. In other words we have to derive the relationship between parameters of the echo signal and of the targets (fish quantity or density), and further to transform an echo signal in such a way that the output of the system produces results proportional to the required items of information.

In order to achieve this task let us follow the transmitted signal, which is transformed by the transducer into sound waves travelling through the seawater until reaching a target (or group of targets), and which is then reflected back toward the transducer, and finally transformed into the electrical signal at the receiver.

3.1 Time Varied Gain

3.1.1 Single target

Let us assume that two identical fish appear within the centre of the beam of the transducer of an echosounder, and that one of the fish is located nearer to the transducer than the other one (Figure 20). It is evident that the echo intensity produced by the fish nearer the transducer will be higher than the echo intensity produced by the fish farther away, because the sound intensity decreases with distance due to spreading and attenuation (see Section 2.3).

Figure 20 portrays the variation of sound intensity at different stages, beginning with the transmission of the sound wave by the transducer and continuing through its propagation through the seawater, reflection by the target, (fish), and travel back to transducer, which converts the received echo into the voltage of the echo at the receiver. signal. The supporting mathematical expressions are given in Figure 20 in the table at the side of the diagram.

In a more detailed description, the sound transmitted by the transducer in the form of pulse of duration τ, travels within the beam width of angle ψ, toward the target. As it was previously explained, the sound intensity decreases with distance according to spreading, i.e. inversely to the squared distance (R^2), and to the exponential function of the logarithmic decrement of attenuation (β) (Section 2.3, formula 7). The target (fish) reflects back part of the energy of the incident sound and thus becomes the source of reflected sound, the intensity of which is proportional to the intensity of incident sound and the scattering cross-section of the target (Section 2.5, formula 12). The reflected sound travels back, and its intensity decreases again with distance according to the propagation law. According to the table in Figure 20, the echo intensity in the neighbourhood of the transducer (I_e) is then proportional to the intensity of the transmitted sound (I_0) and the scattering cross-section of the target (σ), and inversely proportional to the fourth power of range (R^4) and the exponential function of over twice the range ($\exp(2\beta R)$):

$$I_e \sim \frac{I_0}{R^4 \exp\,(2\beta R)}\,\sigma \tag{20}$$

The echo received by the transducer is converted into the voltage on its terminals, according to the properties of the transducer (Section 2.4, formula 8). For a constant transmitted power (I_0 = constant), the voltage (u_e) of an echo signal will be proportional to the square root of the echo intensity I_e, which in turn is directly proportional to the square root of the terms other than I_0 in equation (20):

$$u_e \sim \sqrt{\frac{1}{R^4 \exp\,(2\beta R)}\,\sigma} \tag{21}$$

		TRANSMITTING ↓	RECEIVING ↑
TRANS-DUCER		TRANSMITTED POWER P = const	ECHO SIGNAL $u_e \sim \sqrt{\frac{1}{R^4 \exp(2\beta R)}\sigma}$
SOUND WAVE		TRANSMITTED SOUND I_0	ECHO $I_e \sim \frac{I_r}{R^2 \exp(\beta R)}\sigma$ $= \frac{I_0}{R^4 \exp(2\beta R)}\sigma$
		INCIDENT SOUND $I_i \sim \frac{I_0}{R^2 \exp(\beta R)}$	REFLECTED SOUND $I_r \sim I_i\ \sigma$ $= \frac{I_0}{R^2 \exp(\beta R)}\sigma$

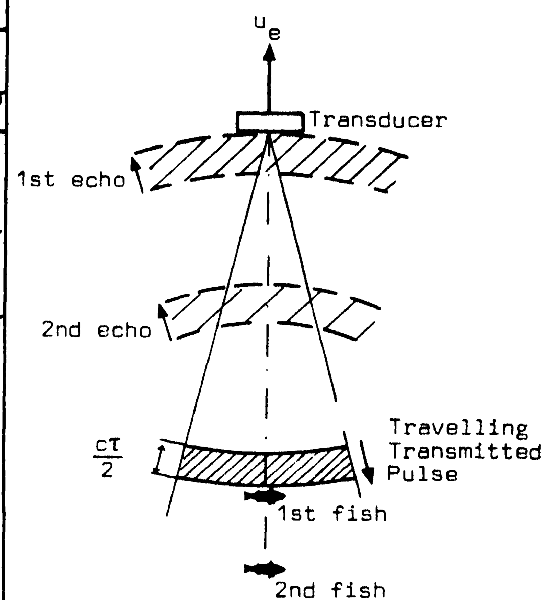


Figure 20 Reflection of an echosounder pulse by two single targets

The received echo signal is then amplified and it drives the display of the echosounder, i.e. a CRT display (oscilloscope) and the paper recorder.[1] An echo signal received from a fish which is located near the transducer will produce a high peak voltage on the CRT and a dark trace on the recording paper of the echosounder. An echo signal received from a fish located far from the transducer will produce a low peak voltage on the CRT and a light trace on the recording paper of the echosounder (Figure 21a). Neither the recorder nor the CRT display give information on the size of fish. We cannot measure directly the target strength or its equivalent cross-section (σ), as those target parameters depend on both the range and the size of a fish and its position in the beam, unless we are considering an idealised beam.

In order to obtain echo signals depending only on the properties of the target, we have to compensate for the decrease in sound intensity due to the propagation laws

$$\left(\frac{1}{R^4 \exp(2\beta R)}\right)$$

This can be done by introducing into the echosounder receiver an amplifier whose effect varies with time (which is directly proportional to range) so that an echo signal received from a range R is multiplied by a factor $[R^4 \exp(2\beta R)]$. This device is called a time-varied gain, usually abbreviated TVG.

With the use of the TVG amplifier, we obtain at the output of the echosounder's receiver echo signals that depend only on the acoustic properties of the target (Figure 21b):

$$u_e \sim \sqrt{\sigma} \qquad (22)$$

The peak signal voltage on the CRT will then be at the same level for the two fish in our example, and the traces on the recording paper will be of the same darkness, independent of the distance between the transducer and each of the individual fish.

3.1.2 Multiple target

Let us assume that a group of fish appears within the transducer's beam and that the transducer has an ideal beam pattern (see Section 2.4.1). The group of fish can be considered as a multiple target.

In order to derive the relationship between the parameters of an echo signal and those of the target, we must consider the variation in the intensity of the transmitted sound as it travels from the transducer to the target, its reflection by the target, and its return to the transducer in the form of an echo, which is converted into an echo signal on the electric terminals of the transducer, as we did in Section 3.1.1 for a single target. The schematic diagram of reflection by a multiple target is shown in Figure 22, and the corresponding mathematical expressions are given in the table at the side of the diagram.

As it was already described, the transmitted electric pulse of duration "τ" is converted by the transducer into a sonic pulse. The intensity of the sound travelling toward the target decreases with distance "R" according to the propagation law (Section 2.3, formula 7), as explained in the discussion of a single target in Section 3.1.1.

[1] The echo signal is amplified by the receiver of the echosounder. For a linear amplifier the signal on the output of the receiver is proportional to the echo signal on the transducer terminals (formula 21).

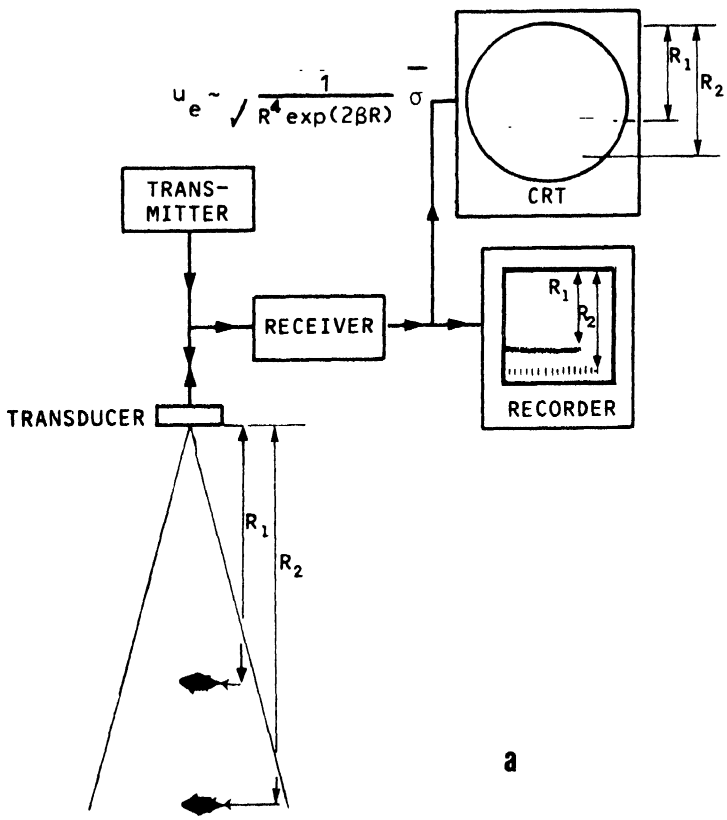


Figure 21 Display of echoes produced by two single targets
(a) echosounder without TVG

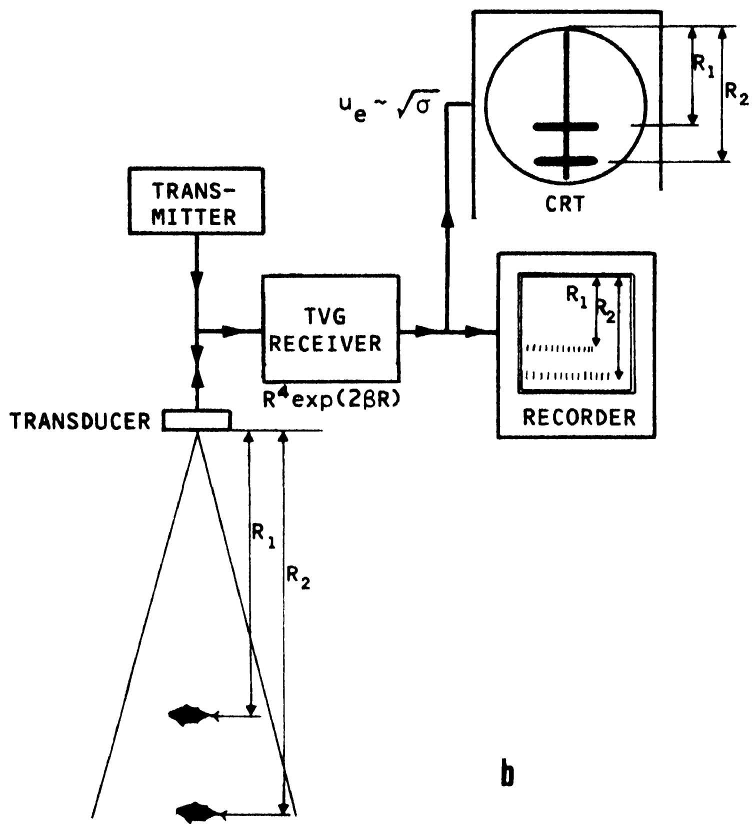


Figure 21 Display of echoes produced by two single targets (continued)
(b) echosounder with TVG

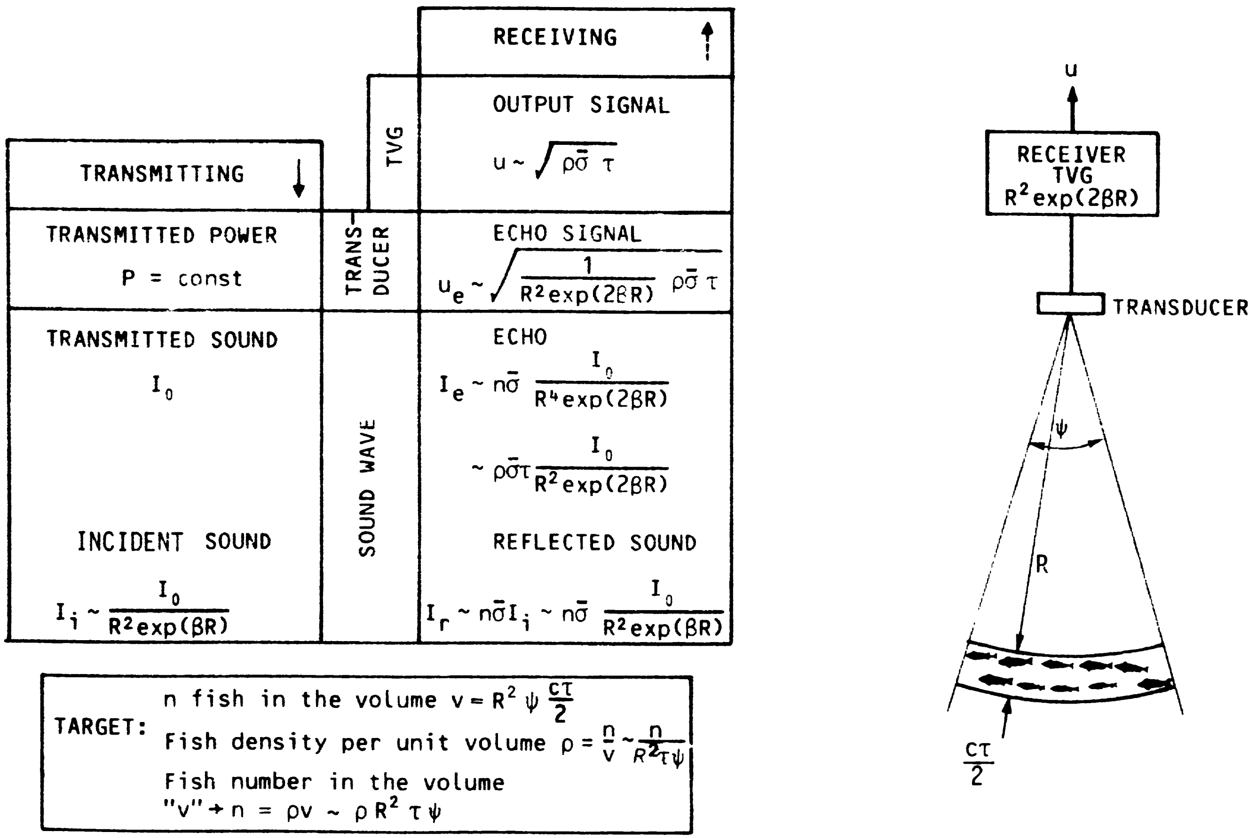


Figure 22 Reflection of an echosounder pulse by a multiple target

Let us consider a thin layer of water of thickness $c\tau/2$. Since the pulse length in the water is $c\tau$, the leading edge of the pulse will reach the bottom of the layer $\tau/2$ units of time after it reaches the top. The reflection of this part of the pulse, travelling back toward the receiver, will pass the top of the layer another $\tau/2$ seconds later, just as the trailing edge of the pulse is being reflected from the top of the layer. At this instant, the sound wave leaving the top of the layer, travelling toward the receiver, will include the reflections of all targets within the volume of thickness $c\tau/2$. It follows that at any instant, the echo intensity at the receiver will represent all targets in a layer of thickness $c\tau/2$ at some range.

Suppose the volume of water within this layer in the beam of the transducer (the solid angle ψ) is occupied by a number n of fish whose average equivalent cross-section is $\bar{\sigma}$. Then, according to equation (16) (Section 2.6), the intensity of the sound wave reflected the fish as a group (multiple target) will be proportional to the incident intensity (I_i), the number of fish (n), and the average scattering cross-section ($\bar{\sigma}$).

The reflected sound travels back toward the transducer and its intensity decreases again with the propagation laws. In terms of proportionality, the intensity of the echo received by the transducer will be:

$$I_e \sim \frac{I_0}{R^4 \exp(2\beta R)} \sum_1^n \sigma_j = \frac{I_0}{R^4 \exp(2\beta R)} n \bar{\sigma} \tag{23}$$

The density (ρ) of targets in the volume of water insonified by pulse, i.e. the volume v with boundaries determined by the beam width (ψ) and the pulse length ($\frac{c\tau}{2}$), will be:

$$\rho = \frac{n}{v} \sim \frac{n}{R^2} \tag{24}$$

where $v = R^2 \psi \frac{c\tau}{2}$, the volume insonified.

Equation (24) can be solved for n:

$$n = \rho v = \rho R^2 \psi \frac{c\tau}{2} \sim \rho R^2 \tau$$

Substituting the last expression into equation (23) gives:

$$I_e \sim \frac{I_0}{R^4 \exp(2\beta R)} \cdot \rho R^2 \tau \bar{\sigma}$$

or

$$I_e \sim \frac{I_0}{R^2 \exp(2\beta R)} \cdot \rho \tau \bar{\sigma} \tag{25}$$

Thus the echo intensity at the transducer is directly proportional to the intensity of the transmitted sound (I_0), the numerical density of fish (ρ), their average scattering cross-section ($\bar{\sigma}$) and the pulse duration (τ), and inversely proportional to the square of range (R^2) and the exponential coefficient of attenuation over twice the range ($\exp(2\beta R)$).

The echo received by the transducer is converted into the voltage on its terminals according to the transducer's properties (Section 2.4, formula 8). For a constant transmitted power, the voltage of the echo signal will be proportional to the square root of intensity, or:

$$u_e \sim \sqrt{\frac{1}{R^2 \exp(2\beta R)} \rho \bar{\sigma} \tau} \qquad (26)$$

In order to obtain an echo signal which depends only on the properties of the target we have to compensate for the decrease of sound intensity due to the propagation laws. This can be done by introducing a TVG amplifier, as discussed in Section 3.1.1 for a single target, but in this case the multiplier of the TVG amplifier for a multiple target must be $[R^2 \exp(2\beta R)]$.

The output voltage of the echosounder receiver equipped with such a TVG amplifier depends on fish density (ρ), on an average scattering cross-section per fish ($\bar{\sigma}$), and on pulse length (τ):

$$u_e$$

For a constant pulse length, the output voltage depends only on the fish density (ρ) and the average scattering cross-section per fish ($\bar{\sigma}$):

$$u_e \sim \sqrt{\rho \bar{\sigma}} \qquad (27)$$

The expression shows that the amplitude of the echo signals observed on the CRT display and the intensity (darkness) of echo traces on the recording paper of the echosounder are directly related to the observed fish density and the size and species of the fish.1/ Consequently, the appearance of a dense aggregation of fish will produce dark traces on the recording paper, whereas the occurrence of an aggregation of the fish of the same size and species, but of low density, will only produce light traces independent of range.

3.1.3 Summary

Two TVG functions were described above: $[R^4 \exp(2\beta R)]$ for single targets and $[R^2 \exp(2\beta R)]$ for multiple targets. The former produces an identical system response to identical targets independent of their distance from the transducer and is therefore useful for studying the target strenth of individual fish.2/ However, since the beam of an echosounder is conical, increasing with depth, the $[R^4 \exp(2\beta R)]$ function produces a much larger system response to a layer of fish of a given density if it occurs at some depth, than it does when it appears near the transducer, since when the layer is deep, many more fish appear within the beam. The $[R^2 \exp(2\beta R)]$ function produces an identical system response to equal densities of fish, regardless of depth. This is essential both for biomass estimates and commercial fishing, and consequently this is the TVG setting most often used by scientists and fishermen.

3.2 Effect of Directivity Pattern

In the previous sections, in our consideration of the reflection of an echosounder's pulse by single and multiple targets, we simplified our model by assuming that the transducer had an ideal beam pattern (i.e. uniform directivity) and that the reflecting directivity pattern of fish was spherically uniform. But as was mentioned before, the transducers of commercially-produced echosounders do have a given directivity pattern that can be far from the ideal one (Section 2.4.1), and fish are not uniformly reflecting targets, but have a reflecting directivity pattern of a certain shape (Section 2.10). In this section the effect of the transducer's directivity pattern and the reflecting directivity pattern of fish will be discussed.

1/ The scattering cross-section of a fish ($\bar{\sigma}$) depends on its size and species (see Section 2.10)

2/ Measurements of target strength of individual fish are described by Forbes and Nakken (1972)

3.2.1 Effect of the transducer directivity pattern

The effect of the transducer directivity pattern can be compared to that of a searchlight. As we know by experience, when illuminating with a searchlight a surface perpendicular to the light rays, we can observe rings of different light intensity (Figure 23a). In the centre of the searchlight beam a light ring of high intensity appears, and further from the centre the intensity of the light decreases.

The same effect can be observed in a cross-section of the insonified volume within a transducer's beam (Figure 23b).

Let us assume for the sake of simplicity that a fish is a uniformly reflecting target. If we place the fish in the centre of the transducer's beam at a range (R), it will reflect a sound wave of maximum intensity "I_{r0}", because the transducer radiates sound of maximum intensity along its acoustic axis (radiated intensity is proportional to the vector "b_0"). If we move the same fish to the side of the transducer's axis, at the same range (R) it will reflect a sound wave of lower intensity "I_{r1}", because the sound wave transmitted by the transducer is of lower intensity at bearing (radiated intensity is proportional to the vector "b_1").

In Section 2.4.1 we mentioned that the transmitting and receiving directivity patterns of a transducer are the same. According to our notation a one-way (i.e. either transmitting or receiving) directivity pattern function is $b = b\ (\theta,\phi)$; therefore a two-way (i.e. transmitting and receiving) directivity pattern function will be $b^2 = b^2\ (\theta,\phi)$. This means that the echo signal received by the transducer should be corrected by a factor $b^2\ (\theta,\phi)$, where θ,ϕ are the angular coordinates of the target, to compensate for the transducer's directivity.

Finally we can correct our previous model of reflection by a single target (Section 3.1.1, Figure 20 for the transducer's directivity pattern. The echo intensity can be obtained by multiplying the right side of proportion (20) by the corresponding value of the two-way directivity pattern function of the transducer $[b^2]$

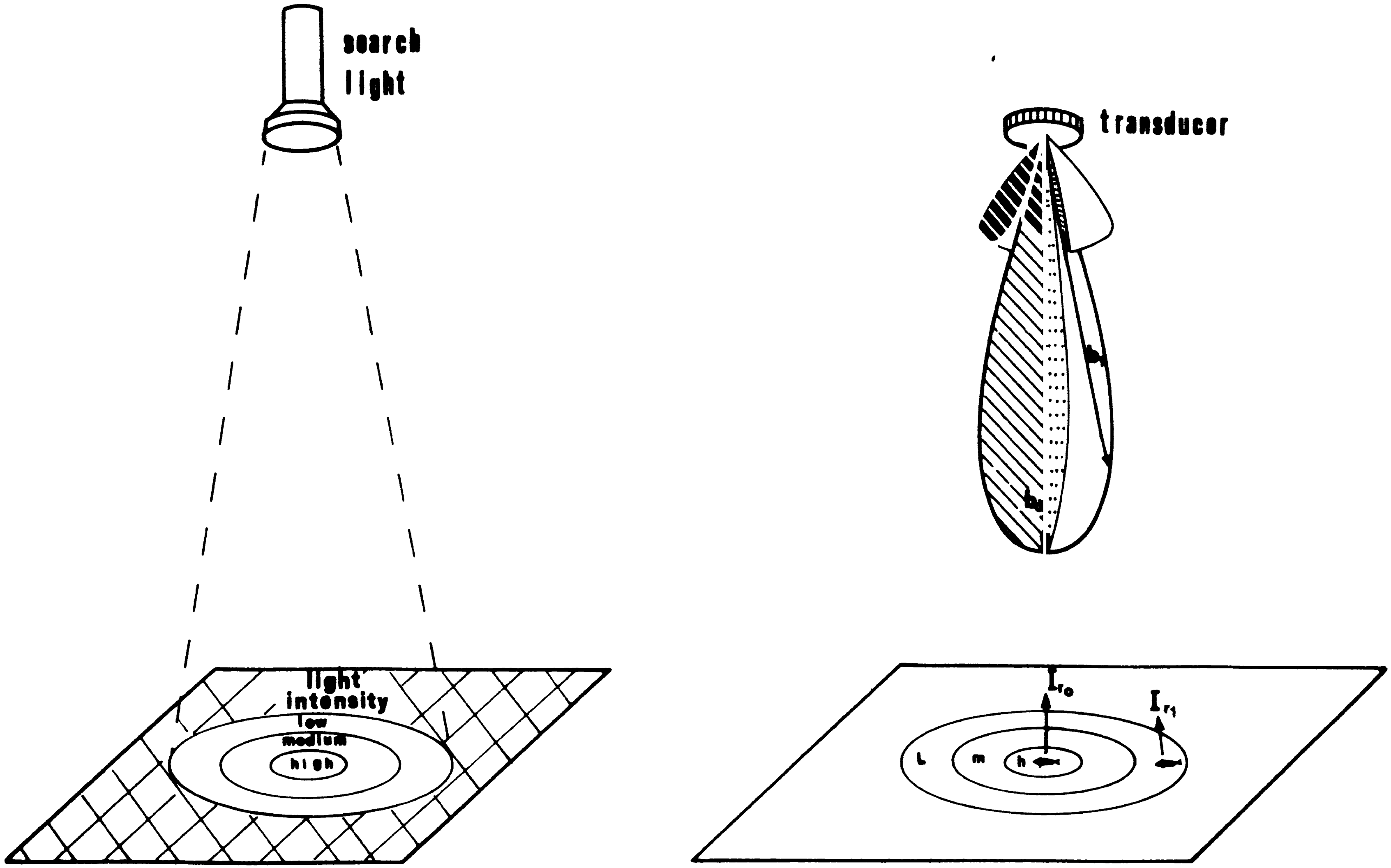
$$I_e \sim \frac{I_0}{R^4 \exp\ (2\beta R)}\ \sigma\ b^2 \tag{28}$$

where

I_e	=	echo intensity received by the transducer
I_0	=	intensity of the sound wave transmitted by the transducer in the direction of its acoustic axis
R	=	distance between the transducer and the target
β	=	logarithmic decrement of the attentuation
σ	=	the scattering cross-section of the target
$b^2 = b^2(\theta,\phi)$	=	the value of the two-way directivity pattern function of the transducer, at a bearing of (θ,ϕ) (i.e. bearing of the target)

The echo received by the transducer is converted into a voltage signal (u_e) at its terminals, and the expression previously obtained for this voltage (formula 21) can now be corrected for the transducer's directivity pattern. For a constant transmitted power the echo signal will be:

$$u_e \sim \sqrt{\frac{1}{R^4 \exp\ (2\beta R)}}\ \sigma\ b \tag{29}$$



a

b

Figure 23 Simplified diagrams of beam patterns
(a) searchlight (b) transducer

If we compensate the two-way transmission loss by introducing into the echosounder the TVG function $R^4 \exp(2\beta R)$, we obtain at the output of its receiver an echo signal which depends on the acoustic properties of the target (σ) and the transducer's directivity pattern function (b):

$$u_e \sim \sqrt{\sigma}\ b \tag{30}$$

For fish of a given scattering cross-section (σ) the output echo signal will vary with the bearing of the target according to the directivity pattern function (b) which measures the variation in transducer performance with bearing. If a fish appears in the centre of the beam we obtain an echo signal at the maximum level, because the directivity pattern function has a maximum value at this bearing ($b_0 = 1$). The further the fish is from the axis of the transducer, the lower will be the echo signal level, due to the decrease of $b = b(\theta,\phi)$ at bearings away from the axis (see Figure 23). Since the echosounder output provides no information on the bearing of the target, there is no simple way to compensate for this variation.

Let us now consider the effect of the transducer's directivity pattern on reflection by a multiple target. As in Section 3.1.2 (Figure 22), consider a layer of water of thickness equal to $\frac{c\tau}{2}$ (c = sound velocity, τ = pulse duration). Let the volume of this layer within the main beam width of the transducer be occupied by the number (n) of fish, of the average scattering cross-section ($\bar{\sigma}$). The contribution of the side lobes is negligible, see Figures 9 and 10b). According to Section 2.6, the sound wave reflected by a multiple target is the sum of the reflections by the individuals each having a scattering cross-section of (σ_j), which may differ. Therefore, as in proportion (23) we can express the echo intensity received by the transducer as:

$$I_e \sim \frac{I_0}{R^4 \exp(2\beta R)} \sum_1^n \sigma_j\, b_j^2 \tag{31}$$

where σ_j = scattering cross-section of the j-th target

$b_j^2 = b^2(\theta_j,\phi_j)$ = the value of the two-way directivity pattern function, corresponding to the bearing (θ_j,ϕ_j) of the j-th target

n = number of fish within the pulse shell of thickness $c\tau/2$

I_e, I_0, R, β = as above

The density of fish in the volume of water insonified by the pulse, i.e. the pulse shell of thickness ($\frac{c\tau}{2}$) within the transducer's beam width of solid angle (Ω_m) will be:

$$\rho = \frac{n}{v} \tag{32}$$

where,

$$v = R^2\, \Omega_m\, \frac{c\tau}{2} \tag{33}$$

Let us consider the average incremental echo intensity produced by (Δn) fish, appearing in a portion of the pulse shell of incremental volume (Δv), bounded by the layer thickness $\frac{c\tau}{2}$ and an increment ($\Delta\Omega$) of the beam angle (Figure 24a). The average number of fish in this incremental volume will be:

$$\Delta n = \rho \, \Delta v \tag{34}$$

or $$\Delta n = \rho \, R^2 \, \frac{c\tau}{2} \, \Delta\Omega \tag{35}$$

which can be expressed in terms of proportion as:

$$\Delta n \sim \rho \, R^2 \, \tau \, \Delta\Omega \tag{36}$$

If the fish have roughly the same average scattering cross-section ($\bar{\sigma}$), then according to proportion (31) the average echo intensity produced by the incremental volume (Δv) will be:

$$\Delta I_e \sim \frac{I_0}{R^4 \exp(2\beta R)} \, \Delta n \, \bar{\sigma} \, b^2 \tag{37}$$

where b^2 = the average value of the transducer's two-way directivity pattern function in the direction of the incremental volume (Δv)

By substituting proportion (36) for (Δn), we obtain:

$$\Delta I_e \sim \frac{I_0}{R^2 \exp(2\beta R)} \, \rho \, \bar{\sigma} \, \tau \, b^2 \, \Delta\Omega \tag{38}$$

The total echo produced by the pulse shell within the whole beam (see Figure 24b) can be written as the sum of increments constituting the whole solid angle Ω_m:

$$I_e = \sum_{\Omega_m} \Delta \, I_e \tag{39}$$

which according to proportion (38) can be expressed as:

$$I_e \sim \frac{I_0}{R^2 \exp(2\beta R)} \, \rho \, \bar{\sigma} \, \tau \sum_{\Omega_m} b^2 \, \Delta\Omega \tag{40}$$

The expression can be written as above in terms of small increments of the solid angle ($d\Omega$), or in terms of calculus as:

$$I_e \sim \frac{I_0}{R^2 \exp(2\beta R)} \, \rho \, \bar{\sigma} \, \tau \int_{\Omega_m} b^2 \, d\Omega \tag{41}$$

This integral $\int_{\Omega_m} b^2 \, d\Omega = \Omega_0$

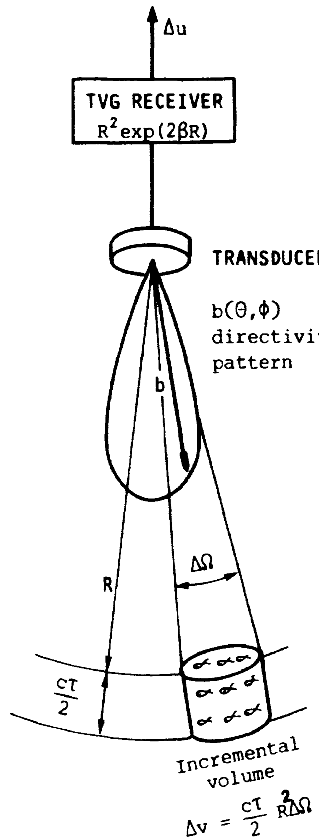
is a constant for a given transducer, and it corresponds to the solid angle of an equivalent ideal transducer (Urick, 1975). Hence, the total echo produced by the sampled layer of thickness $c\tau/2$ within the transducer's beam will be:

$$I_e \sim \frac{I_0}{R^2 \exp(2\beta R)} \, \rho \, \bar{\sigma} \, \tau \, \Omega_0 \tag{42}$$

TRANSMITTING	TVG / TRANS-DUCER	RECEIVING
	TVG	OUTPUT SIGNAL $\Delta u \sim \sqrt{\rho \bar{\sigma} \tau b^2 \Delta\Omega}$
TRANSMITTED POWER P = const.	TRANS-DUCER	$\Delta u_e \sim \sqrt{\rho\bar{\sigma}\tau \frac{1}{R^2 \exp(2\beta R)} b^2\Delta\Omega}$
TRANSMITTED SOUND $I_0\, b$		ECHO $\Delta I_e \sim \Delta n \bar{\sigma} \frac{I_0}{R^4 \exp(2\beta R)} b^2$ $\sim \rho \bar{\sigma} \frac{I_0}{R^2 \exp(2\beta R)} b^2 \Delta v$ $\sim \rho \bar{\sigma} \tau \frac{I_0}{R^2 \exp(2\beta R)} b^2 \Delta\Omega$
INCIDENT SOUND $I_i \sim \frac{I_0}{R^2 \exp(2\beta R)} b$		REFLECTED SOUND $\Delta Ir \sim \Delta n \bar{\sigma} I_i$ $\sim \Delta n \bar{\sigma} \frac{I_0}{R^2 \exp(2\beta R)} b$

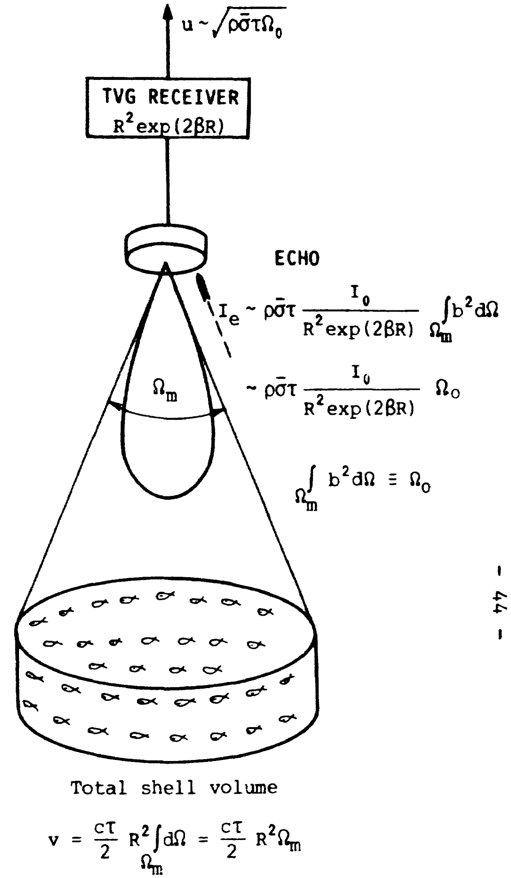
TARGET:

a	b
Δn fish in unit volume Δv	n fish in unit volume v
Fish density per unit volume: $\rho = \frac{\Delta n}{\Delta v}$	$\rho = \frac{n}{v}$



Number of fish in the incremental volume: $\Delta n = \rho\Delta v \sim \rho R^2 \tau\Delta\Omega$

a



Total shell volume

$$v = \frac{c\tau}{2} R^2 \int_{\Omega_m} d\Omega = \frac{c\tau}{2} R^2 \Omega_m$$

Number of fish in the shell volume: $n = \rho v \sim \rho R^2 \tau \Omega_m$

b

Figure 24 Reflection of an echo sounder pulse, from a transducer of directivity pattern $b(\Theta,\phi)$, by a multiple target
(a) the incremental volume of pulse shell (Δv) within an incremental solid angle ($\Delta\Omega$)
(b) the total volume of the pulse shell (v) within the beam angle (Ω_m)

The echo received by the transducer is converted into the voltage on its terminals (Section 2.4, formula 8), and for a constant transmitted power, the echo signal will be:

$$u_e \sim \sqrt{\frac{1}{R^2 \exp(2\beta R)} \rho \bar{\sigma} \tau \Omega_0} \tag{43}$$

If we equip the echosounder with the TVG function $[R^2 \exp(2\beta R)]$, the signal at the output of the receiver will be independent of range:

$$u_e \sim \sqrt{\rho \bar{\sigma} \tau \Omega_0} \tag{44}$$

For a constant pulse duration (τ) and a particular transducer of a given equivalent beam angle (Ω_0), the output voltage depends only on the fish density (ρ) and the average scattering cross-section per fish ($\bar{\sigma}$):

$$u_e \sim \sqrt{\rho \bar{\sigma}} \tag{45}$$

Finally we have obtained the same proportional relationship as in the case of a transducer with an ideal beam pattern (Section 3.1.2, expression 27), in effect by averaging the real beam pattern. (Although the same basic proportions hold in both cases, some of the terms in the complete equations for echo intensity are different for ideal and real beam patterns).

3.2.2 Combined effect of the transducer and fish directivity patterns

The combined effect of the fish and the transducer directivity patterns can be considered as in Section 3.2.1. Assume that a single horizontally-swimming fish with reflecting directivity pattern $b_f = b_f(\theta,\phi)$ and a scattering cross-section from its dorsal aspect σ_0 appears within the transducer's beam at a distance R (Figure 25). The echo intensity at the transducer will depend on the two-way transmission loss and the product of the two-way directivity function of the transducer and the one-way directivity function of the fish:

$$I_e \sim \frac{I_0}{R^4 \exp(2\beta R)} \sigma_0 b^2 b_f \tag{46}$$

where σ_0 = the scattering cross-section of the fish from its dorsal aspect

$b_f = b_f(\theta,\phi)$ = the value of the fish reflecting directivity function at the bearing (θ,ϕ)

I_e, I_0, R, β, b = as above

If we use an echosounder with TVG function $[R^4 \exp(2\beta R)]$, the output signal of the receiver will be independent of the range, and as in equation (30) we can write:

$$u_e \sim \sqrt{\sigma_0} \tag{47}$$

If a horizontally-swimming fish appears in the centre of the transducer's beam, it will produce an echo at the maximum level, as both the transducer and the fish directivity functions reach the maximum in this case (Figure 25a). The further the fish is from the centre of the transducer, the lower will be the echo signal level, owing to the decrease of the directivity functions b and b_f (Figure 25b).

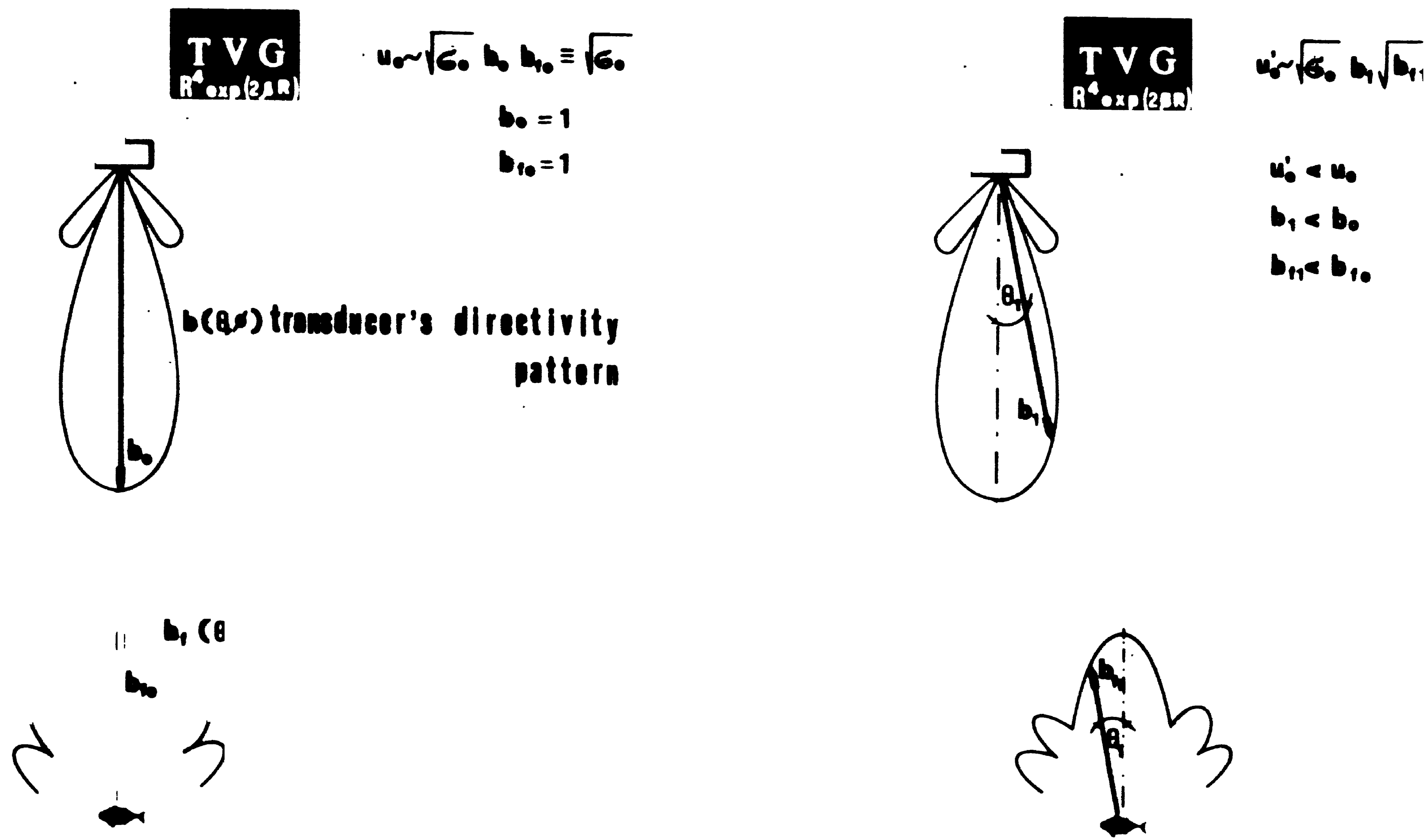


Figure 25 C ned effect of the directivity patterns of the transducer and fish
(a fish located on the acoustic axis of the transducer ($b_0 = 1$), insonified in the direction of the maximum reflecting directivity pattern ($b_{f0} = 1$)
fish located to one side of the transducer's axis and insonified from the side

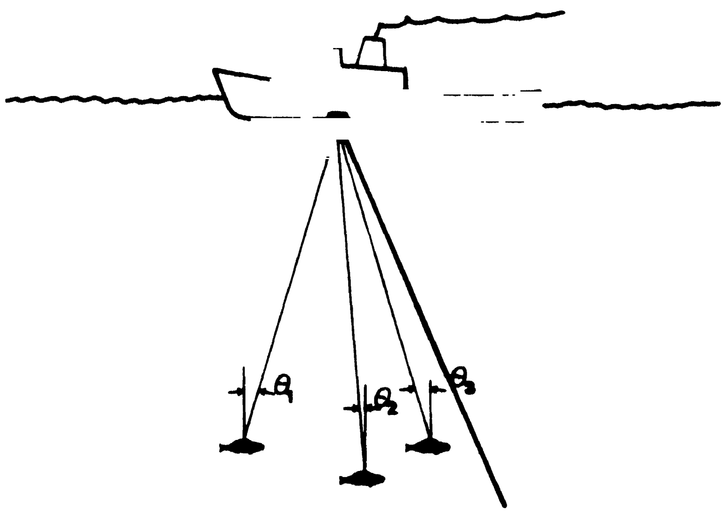


Figure 26   Observation angle of fish by an echosounder

We can also consider the combined effect of directivity patterns for a multiple target as we did in Section 3.2.1. The echo intensity received by the transducer will be the sum of the echoes originated by reflections by the individuals; hence, as in equation (31) we can write:

$$I_e \sim \frac{I_0}{R^4 \exp(2\beta R)} \sum_1^n \sigma_{0j} \, b_{fj} \, b_j^2 \tag{48}$$

where σ_{0j} = the scattering cross-section of the j-th fish from its dorsal aspect

b_{fj} = the value of the reflecting directivity function of the j-th fish

and remaining symbols as in (31)

Let us proceed to a consideration of the sampled volume occupied by (n) fish as in Section 3.2.1. If the fish are roughly the same size and shape and if they are swimming almost horizontally, we can introduce the average "directional" cross-section of the fish, i.e. the average cross-section of (n) fish insonified from different directions (θ_j, ϕ_j) within the transducer's beam:

$$\bar{\sigma}' = \frac{1}{n} \sum_1^n \sigma_{0j} \, b_{fj} \tag{49}$$

Hence, as in equation (42) the total intensity of the echo received by the transducer from the sampled volume will be:

$$I_e \sim \frac{I_0}{R^2 \exp(2\beta R)} \rho \, \bar{\sigma}' \, \tau \, \Omega_0 \tag{50}$$

And finally, the output voltage obtained at the echosounder receiver with TVG $[R^2 \exp(2\beta R)]$ can be expressed as in equation (45):

$$u_e \sim \sqrt{\rho \, \bar{\sigma}'} \tag{51}$$

3.2.3 Conclusions

We can expect that fish are usually positioned horizontally, which is the natural swimming position, with some variation in its tilt angle due to the behaviour patterns of different species. Normally the echo signal will depend on the dorsal aspect scattering cross-section of the fish.

The position of an individual fish may not be vertically below the transducer in the centre of its beam, but it could be anywhere. We do not know whether the sound strikes fish vertically or at any angle θ within the transducer's beam (see Figure 26); therefore when measuring the echo signal level from an individual fish we do not know whether the given echo is produced by a small fish in the centre of the beam or by a big one at the side of the transducer's axis. We can however assume that the average echo intensity produced by the fish is related to the equivalent (or "average") beam width of the transducer and to the average value of the fish scattering cross-section, averaged according to the "observation angle" (θ). The average value of the echo will be lower than the maximum one for a given transducer and for a given fish, but the important point for purposes of making biomass estimates is that this average echo will be proportional to the density of fish in the beam of the transducer, as demonstrated above.

3.3 Echo Integrator

In previous sections it has been shown that an echosounder with TVG function $[R^2 \exp(2\beta R)]$ at any instant produces an output voltage that is proportional to the square root of fish biomass density in a layer of thickness $c\tau/2$ at a range R from the transducer. Now in fact the sound pulse emitted by the transducer travels through a total distance ΔR very much greater than $c\tau/2$ (the total sampled column ΔR depending on the pulse repetition rate), so it remains to be explained how the instantaneous output voltages are combined to produce an estimate of fish biomass density in the entire column ΔR covered by each pulse.

If fish density varies with range (R), it is obvious that the receiver's output voltage will vary accordingly with time. Because the time (t) between transmitting a pulse and receiving an echo is directly related to the distance (R) between the transducer and the target, equation (51) can be written in terms of functions of time and range:

$$u(t) \sim \sqrt{\bar{\sigma}' \rho (R)}$$

If we square this time-dependent signal we obtain a magnitude directly proportional to fish biomass density in the layer of thickness $c\tau/2$:

$$u^2(t) \sim \bar{\sigma}' \rho (R) \tag{52}$$

If we next multiply this magnitude by the thickness of the layer, we obtain a quantity directly proportional to the biomass of fish beneath a unit area of the surface of the layer. And finally, if we add these quantities from all the layers (each of thickness $c\tau/2$) making up the entire sampled column of depth ΔR, we obtain a figure proportional to the total biomass of fish beneath a unit area of the sea surface down to a depth ΔR below the transducer covered by each pulse.

This is the basic idea of the echo integrator. The major difference between the simple description above and the actual operation is that the receiver does not produce a series of discrete values for the sampled column ΔR divided into discrete layers of thickness $c\tau/2$. Instead, it produces a continuous, instantaneous output, which instead of being multiplied by the layer thickness and summed, must be integrated with respect to range over the entire sampled column. The principle is the same, however.

The integrator value for each pulse provides a quantity proportional to fish biomass per unit area of sea surface at that point. The last step in echo integration is to average these readings over the cruise track of the vessel to obtain a quantity proportional to the average areal density of biomass in the whole area surveyed or some part of it. This figure can then be multiplied by the corresponding total area to obtain a magnitude proportional to total fish biomass.

The successive steps of echo integration are shown in Figure 27. First the squared output voltage of the receiver (Equation 52) is integrated over the sampled column ΔR, which corresponds to a certain time interval ΔT, by the first electronic integrator, the integrator per transmission (i.e. per pulse):

$$u^2_{\Delta T} = \int_{\Delta T} u^2 (t)\, dt \sim \int_{\Delta R} \bar{\sigma}' \rho (R)\, dR \tag{53}$$

Hence, the integral of the squared echo signal over the interval of time ΔT, which is produced by fish insonified in the column of water ΔR, can be expressed as:

$$u^2_{\Delta T} \sim \bar{\sigma}'_{\Delta R}\, \bar{\rho}_{\Delta R}\, \Delta R \tag{54}$$

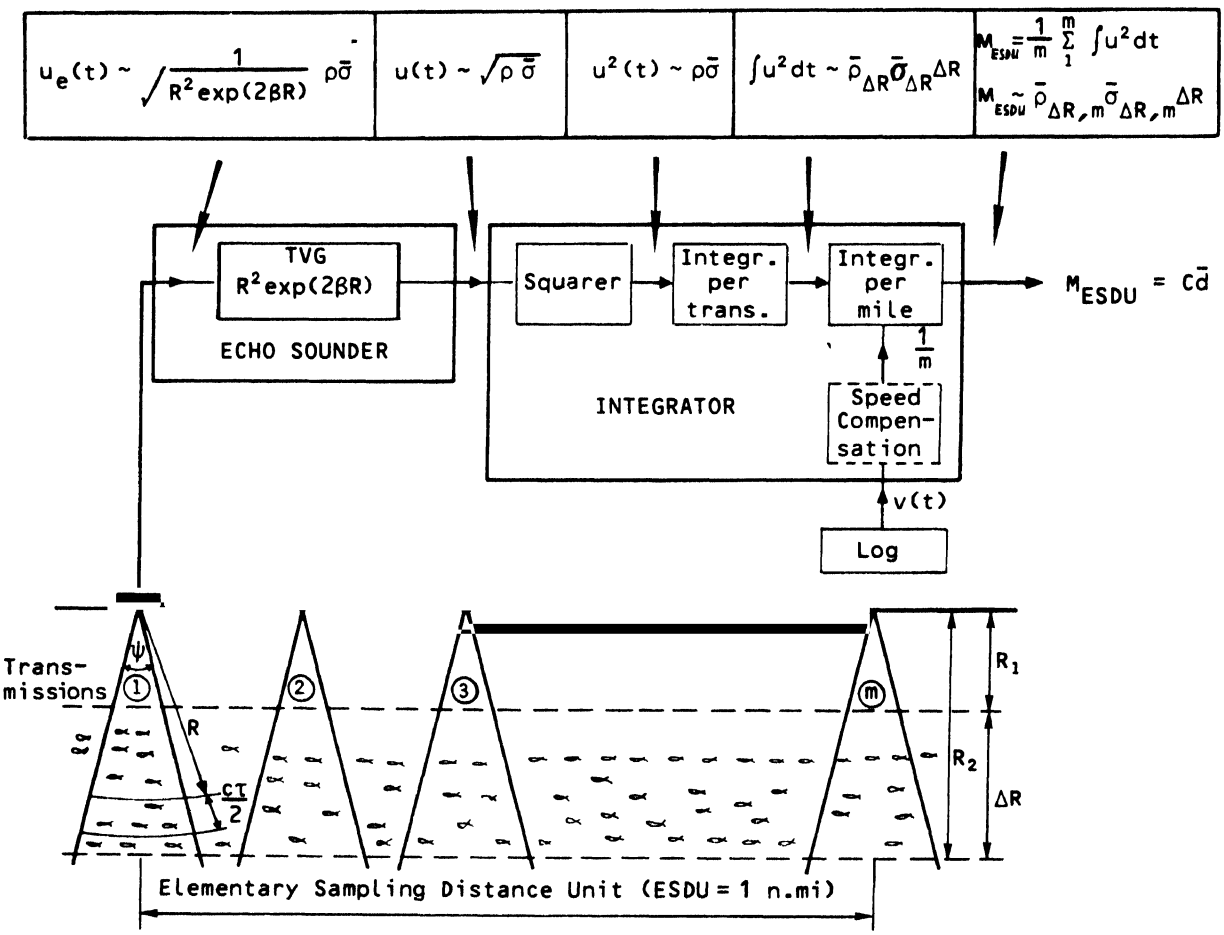


Figure 27   Functioning of the echo integrator

where $\bar{\sigma}'_{\Delta R}$ = average equivalent scattering cross-section of fish in the sampled volume

$\bar{\rho}_{\Delta R}$ = average density of fish in the sampled column of water

ΔR = thickness of the integrated or sampled layer

The average density of fish in the column of water of depth ΔR sampled by the pulse can be expressed as follows:

$$\bar{\rho}_{\Delta R} = \frac{N}{\bar{s}\ \Delta R} \qquad (55)$$

where $\bar{s}$ = average surface area of the sampled volume of water (Figure 28)

N = number of fish in the sampled volume ($V \sim \bar{s}\ \Delta R$)

Hence the product of the average density of fish in the sampled volume and the thickness of the layer ($\bar{\rho}_{\Delta R}\Delta R$) in equation (54) can be interpreted as the average density of fish per unit area of surface or "the areal density of fish":

$$\bar{\rho}_{\Delta R}\ \Delta R \sim \frac{N}{\bar{s}} \qquad (56)$$

By substituting (56) into (54) we obtain:

$$u^2_{\Delta T} \sim \bar{\sigma}'_{\Delta R}\ (\frac{N}{\bar{s}}) \qquad (57)$$

Thus the output signal of the "integrator per transmission" is proportional to the average cross-section of the sampled fish and their areal density in number, i.e. biomass per unit surface.

In order to obtain a magnitude proportional to the average density of fish and its average scattering cross-section for a number (m) of consecutive transmissions, the output signal of the "integrator per transmissions" must be averaged over all (m) transmissions. This operation is executed by the second integrating unit, i.e. "the integrator per mile", which produces the current sum of integrals per transmission. In other words, the second integrating unit sums up the values of the integrated squared output voltage produced by the first integrator:

$$M_m \sim \sum_1^m u^2_{\Delta T_j} \qquad (58)$$

where M_m = output signal of the second integrating unit per (m) transmissions

$u^2_{\Delta Tj}$ = output signal of the first integrator for the j-th transmission

= number of transmissions

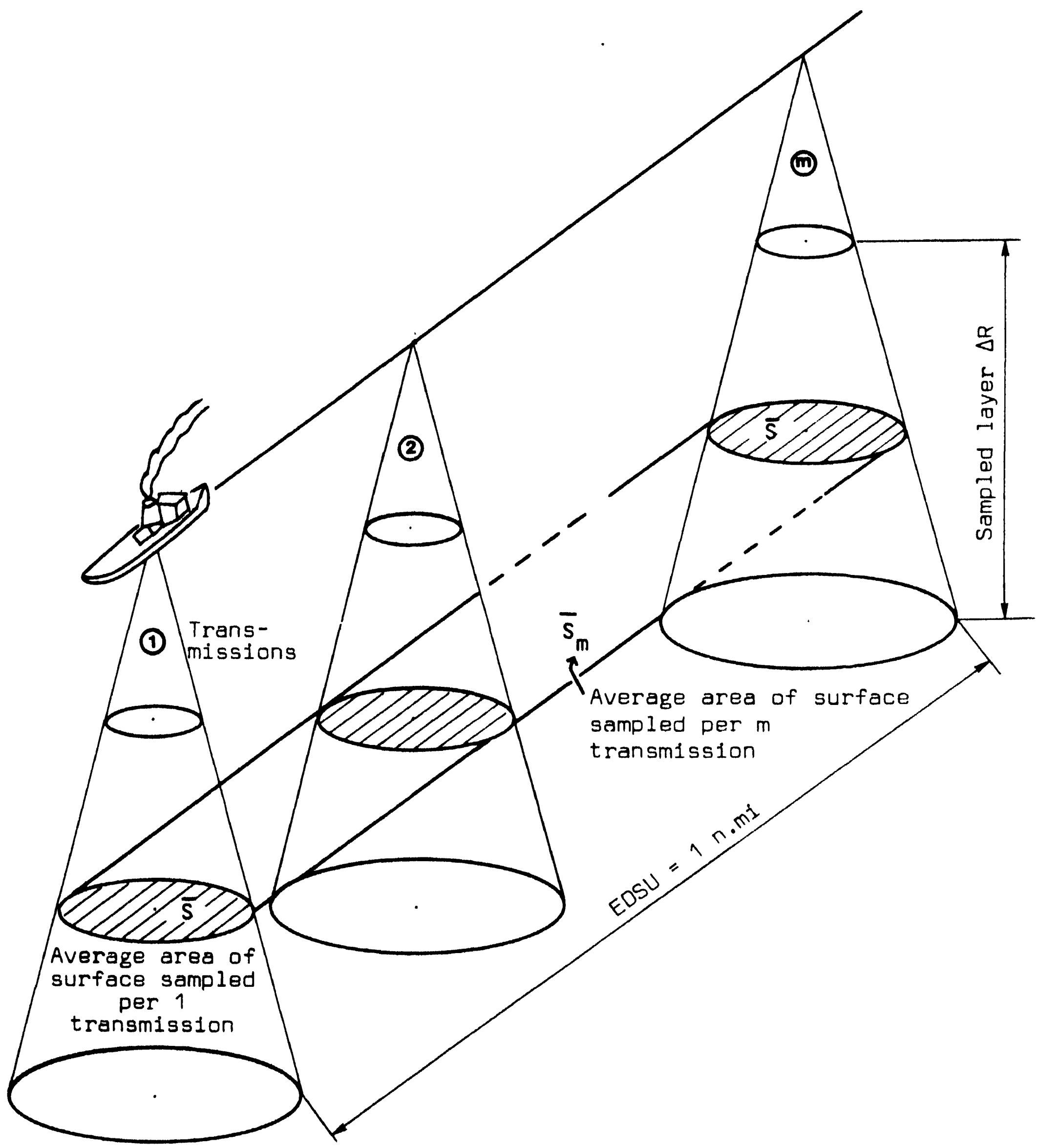


Figure 28 Average surface area sampled by an echo integrator

By substituting (57) into (58) we obtain:

$$M_m \sim \sum_{1}^{m} \bar{\sigma}'_{\Delta R_j} \left(\frac{N}{\bar{s}}\right)_j \tag{59}$$

which can also be expressed as:

$$M_m \sim m\, \bar{\sigma}'_{\Delta R,m} \left(\frac{\dot{N}}{\bar{s}}\right)_m \tag{60}$$

where $\bar{\sigma}'_{\Delta R,m}$ = average scattering cross-section of fish within the sampled volume, during (m) transmissions

$\left(\frac{\dot{N}}{\bar{s}}\right)_m$ = average spatial density of fish appearing within the sampled volume, during (m) transmissions

The pulse repetition rate is a constant for any given range ΔR of the echosounder, so the number of transmissions per unit distance steamed by the vessel will depend on the speed of the vessel. In order to obtain an output signal from the echo integrator strictly related to the distance travelled but independent of the vessel's speed, we must adjust the output signal of the second integrating unit according to the actual speed of the vessel. This function is executed by the speed compensation unit, controlled either manually or automatically by the vessel's log. The output signal of the "integrator per mile" adjusted for the speed of the vessel can be expressed as:

$$M_{ESDU} \sim \frac{1}{m} M_m \tag{61}$$

where M_{ESDU} = average integrator deflection over one ESDU (Elementary Sampling Distance Unit)

m = actual number of transmissions in ESDU

M_m = total output of integrator per mile resulting from (m) transmissions

By substituting formula (60) into (61) we obtain:

$$M_{ESDU} \sim \left(\frac{\dot{N}}{\bar{s}}\right)_m \bar{\sigma}'_{\Delta R,m} \tag{62}$$

Taking into account that the average cross-section of fish ($\bar{\sigma}$) is proportional to the average weight per fish ($\bar{w}$) (see Section 2.10), we can write the following:

$$M_{ESDU} \sim \left(\frac{\dot{N}}{\bar{s}}\right)_m \bar{w} \tag{63}$$

The right side of equation (63) is equal to the biomass of fish per unit surface area. Hence we can write:

$$M_{ESDU} \sim \bar{d} \tag{64}$$

where = average biomass density, i.e. average density of fish in weight per unit area of water, e.g. ($t/n.mi^2$)

If we introduce a simple proportionality coefficient into the above formula, we finally obtain the echo integrator equation:

$$M_{ESDU} = C\bar{d} \tag{65}$$

where M_{ESDU} = average integrator deflection

C = proportionality coefficient

$\bar{d}$ = average biomass density (t/n.mi^2)

It has been proved by various experiments that the above integrator equation is valid for a given species of fish, if the variation in the sizes of fish is not too large. (The scattering cross-section of fish of a given species can be taken as approximately proportional to the weight per fish in this case). However, the integrator output signal might give a good indication of the total biomass density of fish in a survey area even when a number of similar species of different sizes are surveyed.

3.4 Calibration

In order to obtain a quantitative estimate of fish surveyed with a sonar system consisting of an echosounder with TVG and an echo integrator, we have to determine the value of the proportionality coefficient in the echo integrator equation (65), i.e. the value of "C".

One of the most reliable methods for determining the value of the calibration constant is direct calibration on live fish. This method was first described by Johannesson and Losse (1977).

Another method in common use is the "Bergen method", i.e. counting traces of single fish recorded by an echosounder and measuring the amplitudes of returned echo signals on an oscilloscope, in conjunction with echo integrator deflections. By comparing then the data obtained by means of acoustic instruments with catch samples of fish (specifically weight per fish), it is possible to calculate the calibration constant and estimate the surveyed biomass (Forbes and Nakken, 1972).

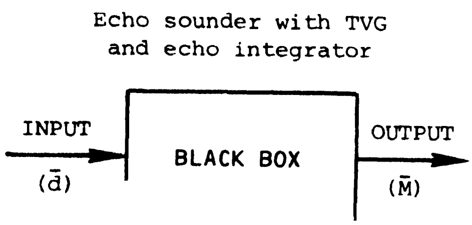
3.4.1 Direct calibration on live fish

Let us consider an acoustic system consisting of an echosounder with TVG and an echo integrator as a "black box" with an input, biomass density ($\bar{d}$), and an output, integrator deflection ($\bar{M}$). We do not know what is inside the black box, but the relationship between input and output can be found experimentally by measuring both at various input levels (Figure 29).

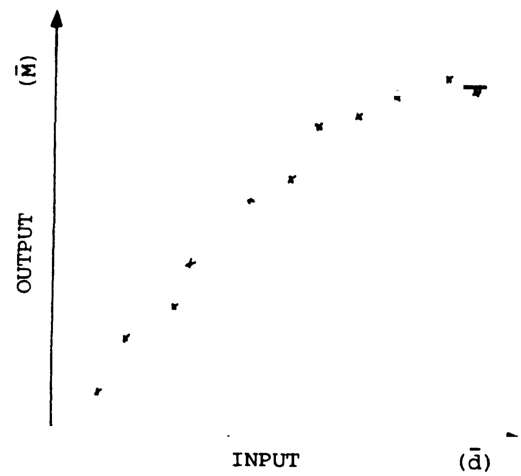
Summarizing, the concept of the direct method of calibration on live fish lies in measuring the value of the integrated echo signal ($\bar{M}$), caused by a known biomass density of fish ($\bar{d}$), and then determining the relationship between ($\bar{d}$) and ($\bar{M}$) from the results of several such experiments. According to the integrator equation (65) we should obtain a proportional relationship between ($\bar{d}$) and ($\bar{M}$).

The arrangement for calibration on live fish is shown in Figure 30. A known quantity of fish is impounded into a special cage, which is placed below the transducer at the centre of its beam. After a repeated number of experiments with different quantities (or densities) of fish, the calibration constant[1/] can be calculated as follows:

1/ The usual form of the calibration constant is given in equation (66). It is the reciprocal of the proportionality coefficient in equation (65), i.e. $C^x = \frac{1}{C}$.



a



b

Figure 29 Concept of calibration on live fish
(a) BLACK BOX
(b) INPUT/OUTPUT relationship

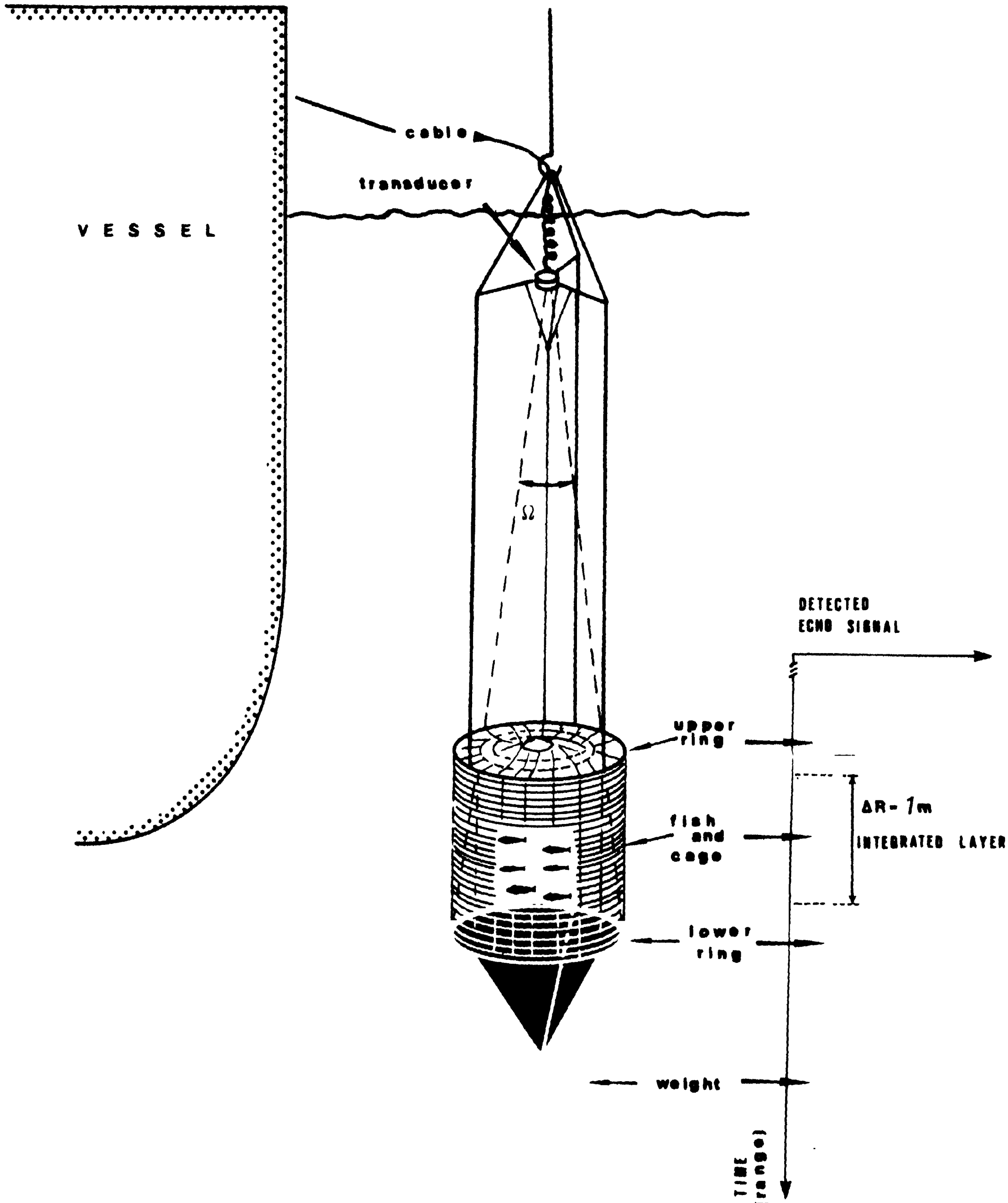


Figure 30 Arrangement for calibration on live fish

$$C^x = \frac{\bar{d}}{\bar{M}} \qquad (66)$$

where $\bar{d}$ = average biomass density for a number of experiments

$\bar{M}$ = average integrator deflection for a number of experiments

The diameter of the cage should be large enough so as to ensure that at any given range within the cage the effective cross-section area of the effective beam (main lobe) should be smaller than that of the cage, assuming that the side lobes effect can be neglected. The minimum distance between the cage and the transducer is limited by two factors:

a) Near field effect (see Appendix 3), i.e. the cage must be placed in the acoustic far field of the transducer.

b) The TVG function, i.e. the cage must be placed at a distance in which the TVG operates properly (for most of the commercially-produced echo-sounders TVG starts at the range about 4 m from the transducer).

Figure 31 shows the example: the dimensions of the cage and the range between the cage and a 120 kHz transducer of diameter 10 cm.

Assuming a uniform distribution of fish in the cage, the average density of fish (per unit volume) can be expressed by:

$$\bar{\rho} = \frac{N}{V} \qquad (67)$$

where N = number of fish in the cage

V = volume of the cage (m^3)

The biomass density of fish appearing in the integrated layer ΔR[1/] can therefore be expressed as follows:

$$\bar{d} = \frac{N\bar{w}}{V} \Delta R \qquad (68)$$

where $\bar{w}$ = average weight per fish (g)

ΔR = 1 m integrated layer (m)

V,N = as above

In order to obtain the biomass density of fish in tonnes per square nautical mile (tonnes/n.mi^2) for convenience of calculation of biomass estimates, the factor 3.43 due to conversion of units from (g/m^2) must be introduced into the above equation:

$$\bar{d} = 3.43 \frac{N\bar{w}}{V} \Delta R \qquad (69)$$

1/ The height of the cage must be greater than the integrated layer ΔR in order to avoid echo signals from the upper and lower ring of the cage. The rings can be made from steel or other rigid material. For the convenience in operating the cage, we use an integrated layer ΔR = 1 m.

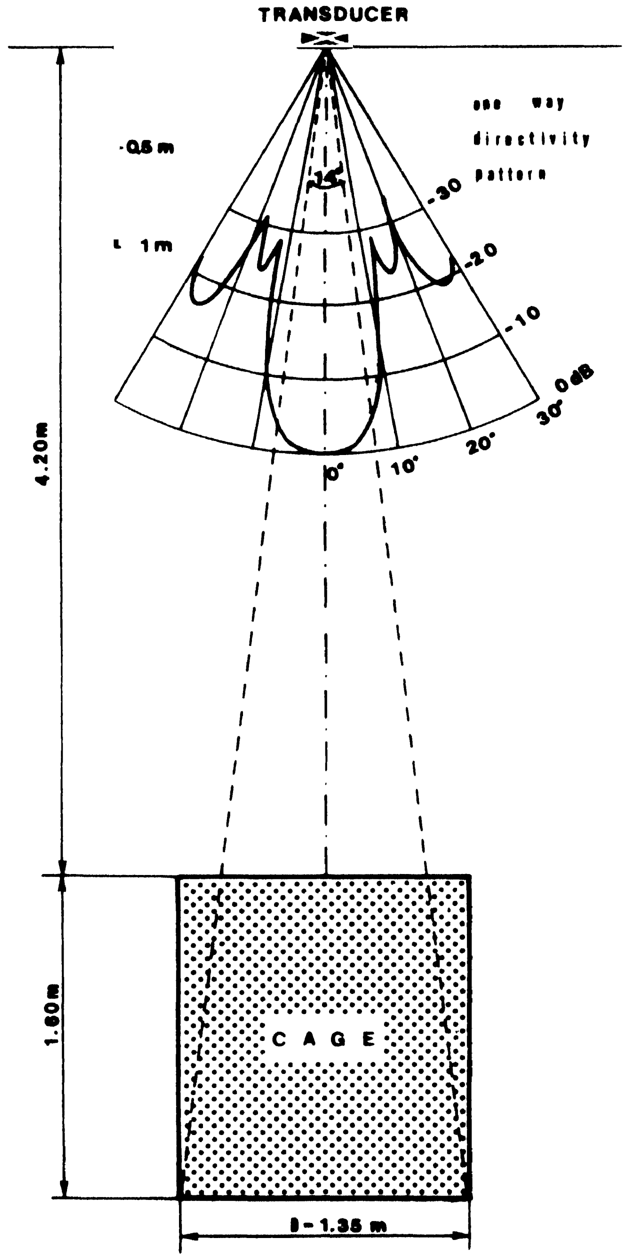


Figure 31 Vertical cross-section of the cage and beam of a 120 kHz transducer of diameter 10 cm

By substituting equation (69) into formula (66), the estimated calibration constant can thus be obtained:

$$C^x = 3.43 \frac{N\bar{w}}{V\bar{M}} \nabla R \tag{70}$$

If a number of experiments are performed with different densities of fish, the value of the calibration constant can be estimated by fitting a linear regression line to the experimental values of the variables M (integrator deflection) and d (biomass density):

$$\bar{M} = ad + b \tag{71}$$

where a = slope of the regression line

b = intercept of the regression line

The calibration constant value can be expressed as the ratio of correlation coefficient in square to the slope of regression line:

$$C^x = \frac{r^2}{a}$$

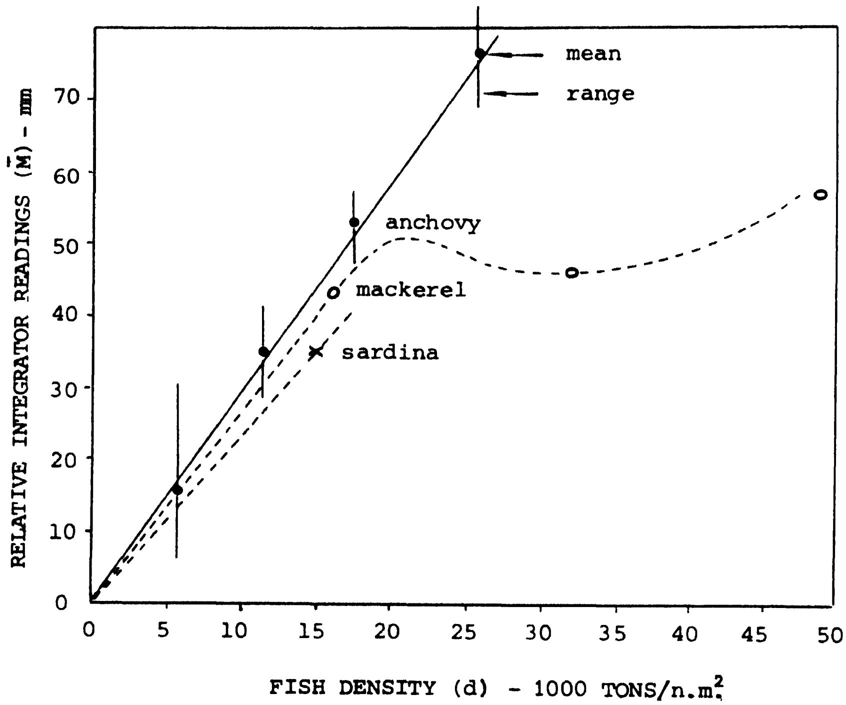
Figure 32 shows an example of the results of direct calibration on various species of fish with a 120 kHz echosounder by Johannesson and Vilchez (1981) at the Acoustic Training Centre in Lima. The results of the experiments are plotted on the graph, i.e. biomass density (d) versus integrator readings (M). The first measurement of echo integrator deflection was taken with the cage empty, i.e. without fish. For each density of fish a number of integrator readings were then recorded and the mean value was calculated. The mean integrator deflection for a given biomass density, reduced for the reading from the empty cage, is denoted on the graph by a thick point. The lines parallel to the (M) axis through the points show the variation of integrator deflection at each density of fish.

The regression line and the calibration constant value presented in the example of Figure 32 were estimated according to the procedure described above. The calculated value of the intercept of the regression line (b = -14.25) is not significant and can be considered zero for practical purposes. In this experiment the regression line fits well (correlation coefficient r = 0.99). However, it can happen that the value of the intercept of the regression line is large, and the regression line does not fit the empirical data well. This indicates that the assumed physical model of calibration does not correspond to reality. It can happen if the cage is not placed in the centre of the transducer's beam (the current diverts the cage from its central position, or the cage is not alligned within the transducer's acoustic axis), or if the fish are not uniformly distributed within the volume of the cage.

The behaviour of the fish and their condition (especially any mortality) must be observed during the experiments (for instance by a diver or underwater camera). The calibration should be carried out after the fish have been allowed to acclimatise for a few hours, first in a keep-net and then in the cage. A purse-seine can be used as a keep-net for the fish (Figure 33).

The central position of the cage can be controlled by observing on the oscilloscope the level of echo signals from reference targets (spheres) placed at the centre of the cage above the upper ring and below the lower ring.

This method of calibration has limitations due to fish behaviour, which in turn depends on species and on density of fish in the cage. According to observations by Johannesson and Vilchez (1981), Burczynski and Azzali (1977), and Rijavec and Burczynski (1977), the integrator deflection and the density of fish are proportional over a certain range of densities. A graph of the patterns of observations is shown in Figure 34:



EXPERIMENT No. 11

Place	:	Isla Lobos de Afuera
Date	:	26 Feb.-2 March, 1979
Vessel	:	R/V SNP-1
Species	:	Anchovy, LT=16.7 cm, W=34.1
		Length range=14.5-18.5

Anchovy

$\bar{d}$	5848	11696	17544	26083
$\bar{M}$	152	343	523	760

$\bar{M} = b\bar{d} + a$

$\bar{M} = 0.0299\bar{d} - 14.25$

$r = 0.99$

$C^x = \frac{r^2}{a} = 32.78$ t/n.mi.^{2}/mm re 1 n.mi.

Figure 32 Results of direct calibration on live fish (Johannesson and Vilchez, 1981)

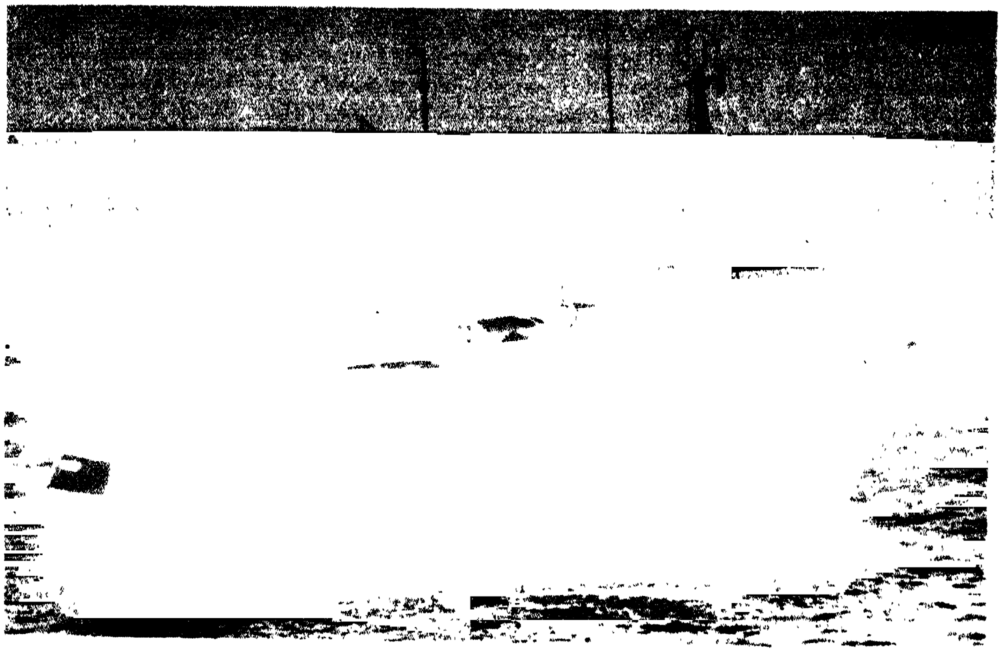


Figure 33   R.V. Sardinella (Cochin) with purse-seine as keep-net

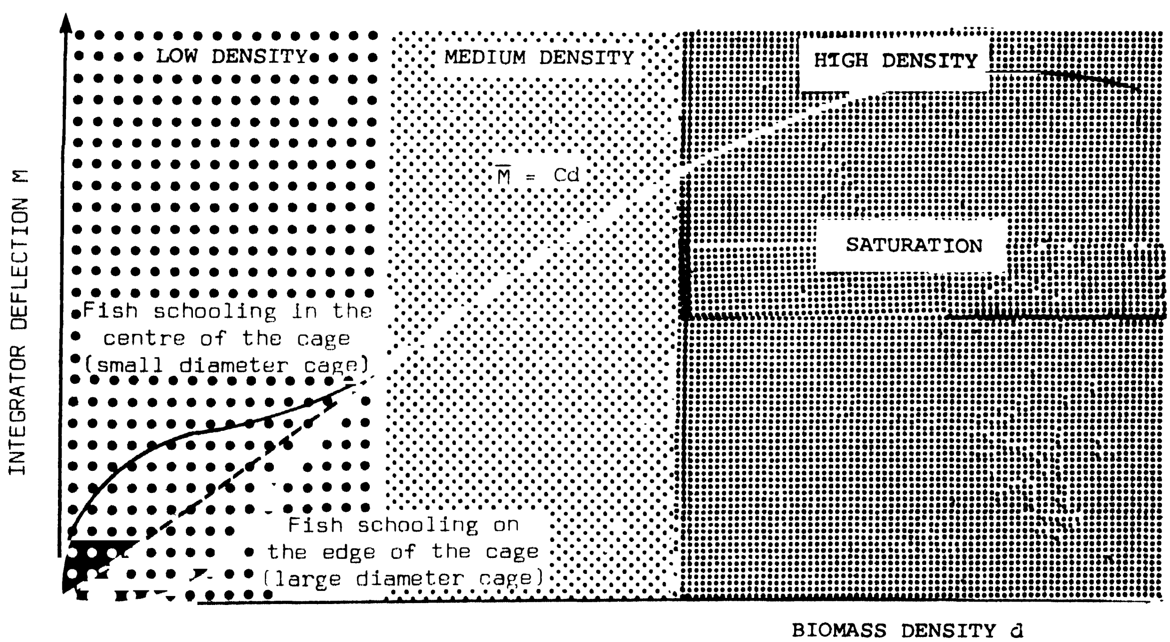


Figure 34   Observed echo integrator readings at low, medium and high biomass densities

(a) Low densities of fish: If the fish do not school but distribute themselves uniformly throughout the cage, there is direct proportionality between the echo integrator deflection (M) and the biomass density (d), (dotted line on the graph). If the fish school at the centre of the cage, the echo integrator readings will be higher than expected from the proportionality law (upper continuous line on the graph). If the fish school at the edge of the cage, the echo integrator readings will be lower than expected (lower continuous line on the graph). All three cases are predictable from the directivity pattern of the transducer.

(b) Medium densities of fish (fish uniformly distributed within the volume of the cage). A proportional relationship is observed between echo integrator deflection (M) and biomass density (d).

(c) High densities of fish: saturation of (M) against (d), a proportion of the fish are swimming horizontally, the remainder, vertically and with the various tilt angles due to high packing density; possible effect of increased attenuation in the environment which consists of sea water and fish bodies and possibly also a secondary reflection effect between individual fish.

Most fish aggregations found in natural conditions, i.e. during surveys, can be classified as having low and medium densities. Hence, the results of calibration on medium and low densities, if variations from proportionality law are not observed, can be directly applied for fish biomass estimates.

If a schooling behaviour pattern within the centre of the cage is observed, which can happen at a low density, we should estimate the average diameter of the school; then the echo integrator readings can be corrected according to the directivity pattern function of the transducer. Let us assume that the transducer's directivity pattern $b^2 = b^2(\Omega)$ is given as in Figure 35a. For a given directivity pattern we can calculate and plot the function $\int b^2 d\Omega$, which portrays the distribution of energy versus the angle $(\frac{\Omega}{2})$ from the transducer's acoustic axis (Figure 35b).

Let us then discuss two cases of the diameter of the cage relative to the beam cross-section:

- In Figure 35c, the diameter of the cage is large and the cage volume exceeds the volume insonified by the transducer within the transducer's beam width (Ωm) and the layer (ΔR).

- In Figure 35d, the diameter of the cage is smaller than the insonified volume within the transducer's beam width (Ωm) and the layer (ΔR).

In the case shown in Figure 35c, we measure the integrated echo from the whole insonified volume, and we can apply the observed values of integrator deflection (M) directly into formula (70) in order to calculate the calibration constant value (C^x).

In the case shown in Figure 35d, we measure the integrated echo from only part of the insonified volume, namely the cone with solid angle Ω_c determined by the dimensions of the cage, and the values of the integrator deflection (M) must be corrected by the factor:

$$k(\Omega_c) = \frac{\int_0^{\Omega_m} b^2 \, d\Omega}{\int_0^{\Omega_c} b^2 \, d\Omega} \qquad (72)$$

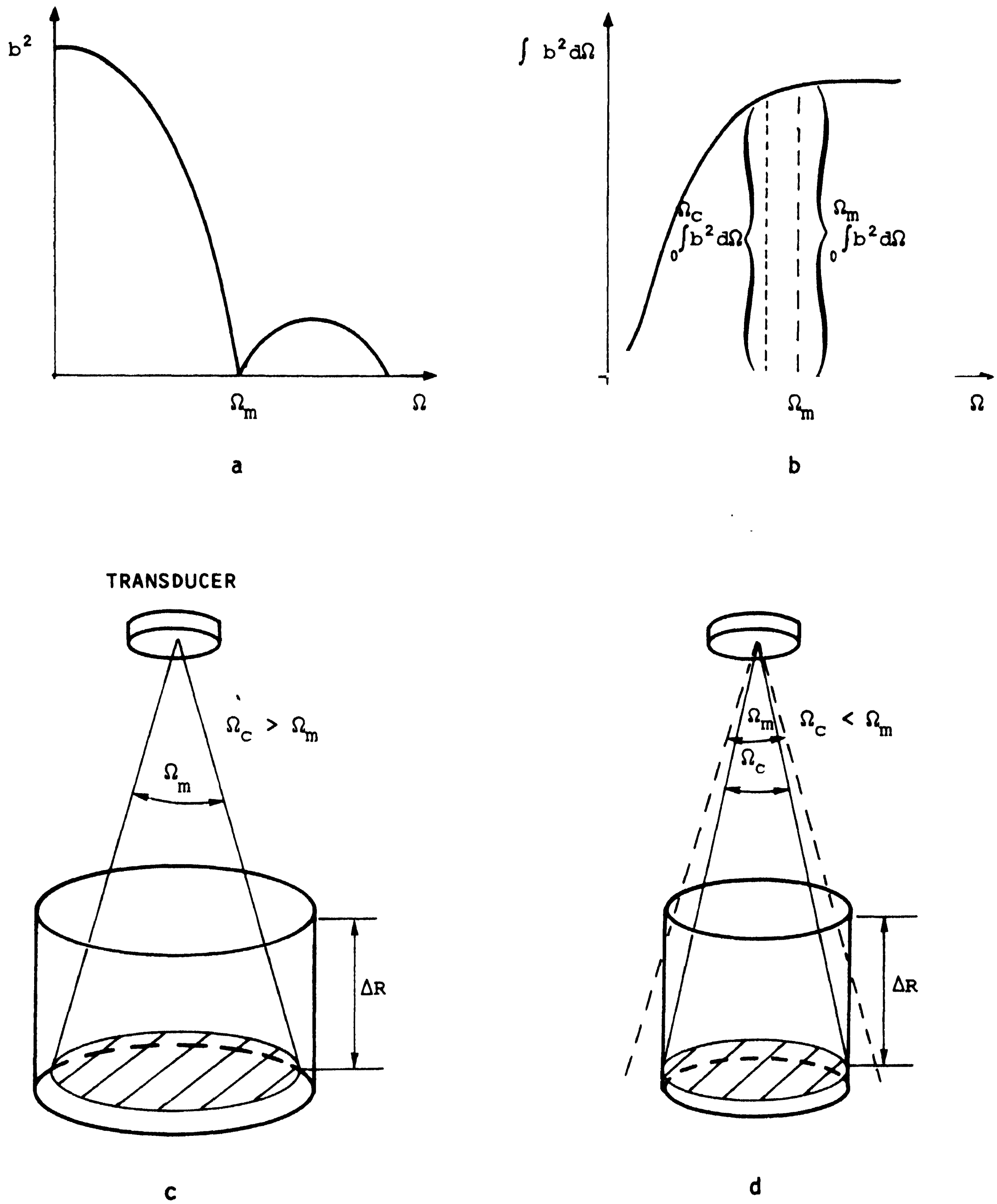


Figure 35 Correction to integrator readings due to transducer's directivity pattern
(a) transducer's two-way directivity pattern
(b) integral of transducer's two-way directivity pattern
(c) large cage
(d) small cage

$$k_\theta = \frac{\int_0^\theta b^2(\theta)\, d\theta}{\int_0^\pi b^2(\theta)\, d\theta}$$

Correction Factor - Half Angle θ

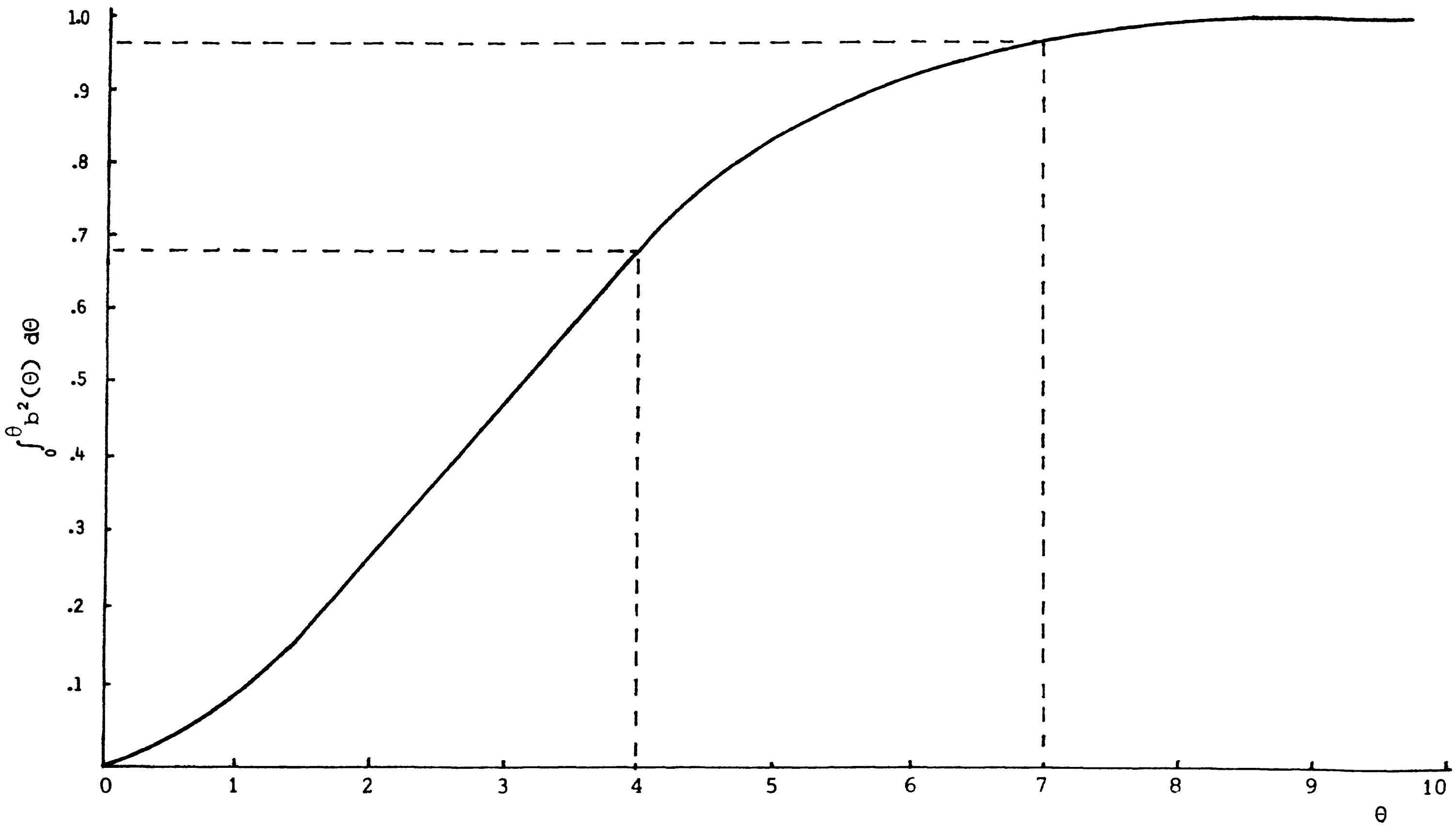


Figure 36   Integrated two-way directivity function for a 120 kHz transducer of 10 cm diameter (by courtesy of J. Edwards and S. Forbes)

to correct for the non-uniform distribution of acoustic energy within the transducer's beam width. Figure 36 portrays as an example the function (k) of the integrated two-way directivity pattern for a SIMRAD 120 kHz transducer 10 cm diameter.

The disadvantage of the method of direct calibration on live fish is that we do not know whether the behaviour of insonified fish is the same for free and caged fish. However, knowledge of the behaviour pattern and specifically the tilt angles of immature fish is rather little, and this is a problem with any method of calibration.

3.4.2 Performance check of equipment

According to the discussion on basic laws of acoustics (Section 2) the value of the echo signal appearing at the output of a sonar system depends, on the one hand, on fish parameters (FP) and, on the other, on sonar system parameters (SSP) (Figure 37). Hence, the estimated value of the calibration constant "C^x" is a function of (FP) and (SSP):

$$C^x = f\left[(FP), (SSP)\right] \tag{73}$$

In other words, the value of the calibration constant obtained by experiment is valid only for the given species of fish, the given size distribution of fish, and the given set of acoustic equipment.

The technical parameters of acoustic equipment can change with time.1/ On the other hand, calibration on live fish is a costly and time-consuming operation, and it can be carried out under special favourable weather conditions (i.e. lack of swell and underwater current). To avoid repeating a calibration, it is best to ensure that estimated fish parameters (FP) from a "master experiment" can be applied for estimating the value of the calibration constant for subsequent acoustic surveys on a given fish species and this is possible provided the actual sonar system parameters (SSP) are known.

Summarizing, we have to measure the values of the parameters of a sonar system (SSP) in order to check that the equipment is working properly, i.e. according to technical specification (if not it must be adjusted), and in order to be able to revise the previously estimated value of the calibration constant if the values of SSP have changed.

The procedure of measuring the SSP is called a "performance check" or "acoustic and electronic calibration of the equipment". An example of a performance check of the equipment and a recalculation of the value of a calibration constant is given in Appendix V. (This material will not be understandable for a beginning reader, but it shows that a good deal of equipment checking has to be done so that acoustic results from different survyes will be accurate and comparable without the need for repeated calibrations on live fish).

The following parameters of the sonar system have to be measured:

1/ Examples: The efficiency of a transducer decreases when the echosounder is not used for a long period of time (especially if a vessel is in a harbour), because of the covering of the transducer's radiating face by shells and marine vegetation (it happens in tropic waters quite fast); the gain of an amplifier or transmitted power can be significantly changed when replacing electronic components of instruments (e.g. transistors), etc.

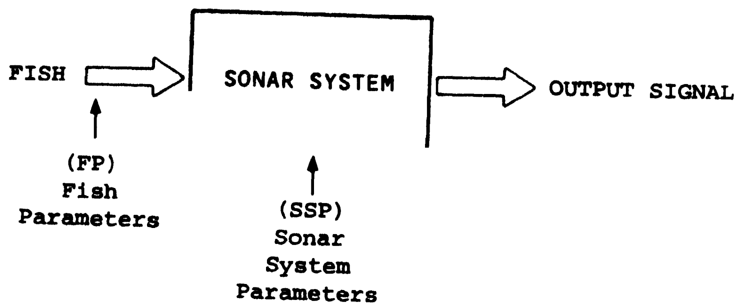


Figure 37 Schematic relation between Fish Parameters (FP), Sonar System Parameters (SSP) and the output signal of the sonar system

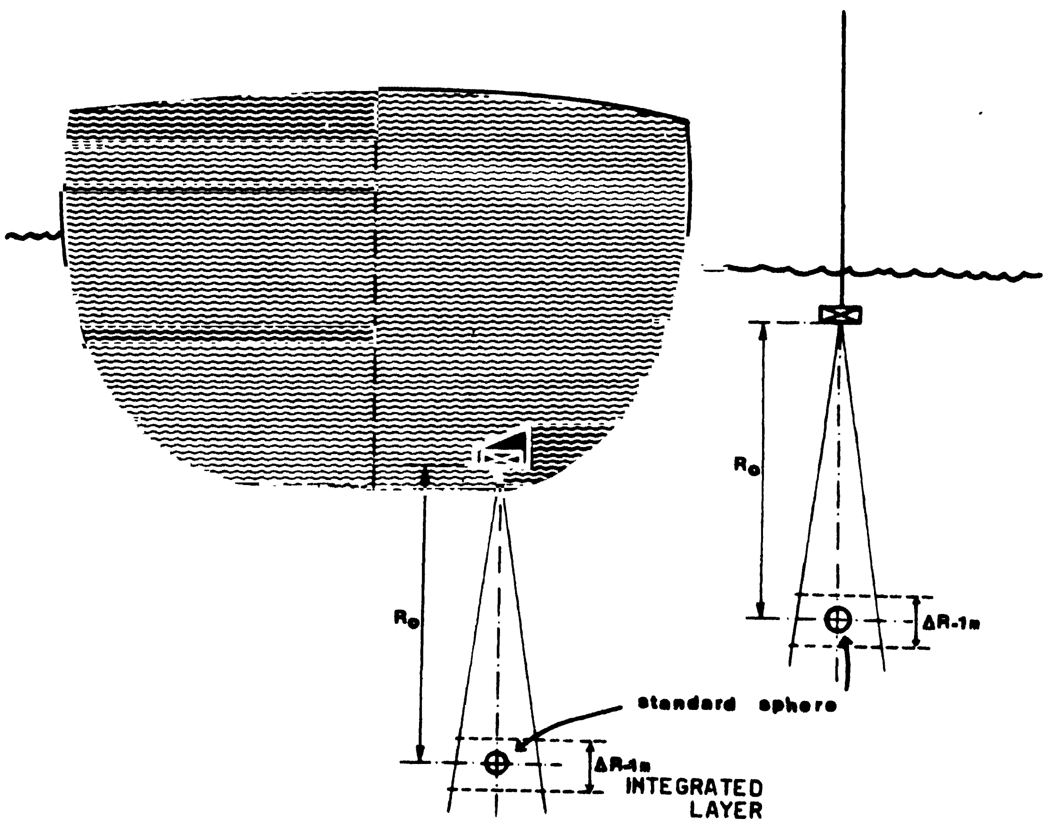


Figure 38 Inter-calibration with a standard target

a) <u>For the echosounder</u>

- the transducer's impedance
- the transmitter's operating frequency
- the transmitter's power, and pulse length
- the source level (SL), which expresses the decibels (dB) of acoustic power radiated by the transducer into the water
- the gain of the receiver
- the system's receiving voltage response (VR), which expresses in decibels (dB) the conversion factor of acoustic energy into electric energy at the transducer's terminals and the receiver's output
- the receiver's bandwidth
- the noise level of a sonar system at various speeds of the vessel, and in various states of the sea, in order to estimate the optimum speed of surveying based on the minimum detected echo signal
- the TVG function; it sometimes happens that the TVG function of a given echosounder is different from the theoretical one and in such a case a correction factor for fish biomass estimates must be introduced

b) <u>For the echo integrator</u>

- the test of the echo integrator recorder, in order to adjust it to the working standard
- the gain of the amplifier for various settings

The performance check of the equipment must be carried out before and after each survey operation and the recorded measurements should be included into the survey report. Only in this way the results of different surveys can be compared.

3.4.3 Inter-calibration with a standard target

Usually calibration procedures are carried out with an external transducer, while echo surveys are carried out using the vessel's hull-mounted transducer. This procedure is recommended for convenience of operation with the cage and the live fish.

The inter-calibration of the two transducers can be done by measuring the integrator deflection for both of them, produced by a standard target, i.e. a sphere placed in the centre of the transducer's beam[1/] and in the middle of the integrated layer (Figure 38). The calibration constant for the vessel's transducer can then be calculated as follows:

$$C_V^x = C_e^x \frac{M_e}{M_V} \qquad (74)$$

1/ The central position of the sphere in the transducer's beam must be carefully watched during experiments.

where C_e^x = the value of calibration constant obtained from experiments on live fish with the external transducer

M_e = the integrator deflection for a period of time corresponding with EDSU = 1 n.mi for the external transducer

M_v = the integrator deflection for a period of time corresponding with EDSU = 1 n.mi for the vessel's transducer

The inter-calibration of transducers with a standard sphere target (Figure 38) has been proved by Johannesson (FAO/Norway/IMARPE Acoustic Training Centre in Lima) to be a method giving reliable results. The value of the calibration constant obtained from results of calibration experiments with a given species, can be recalculated for any other set of equipment installed on the vessel, if the estimated value of "C^x" is referred to the measurements on a standard target. Measurements of the integrator deflection from a standard target should be included as a routine procedure in the performance check of the equipment.

4. REFERENCES

Burczynski, J. and M. Azzali, Report to the Government of Italy on the quantitative acoustic
1977 estimation of sardine stock and distribution in the northern Adriatic Sea. Italian Funds-in-Trust. Rome, FAO, TF-ITA3 (ITA):53 p.

Clay, C.S. and H. Medwin, Acoustical oceanography: principles and applications. New York,
1977 Wiley - Interscience, 544 p.

Forbes, S.T. and O. Nakken, Manual of methods for fisheries resource survey and appraisal.
1972 Part 2. The use of acoustic instruments for fish detection and abundance estimation. FAO Man.Fish.Sci., (5):138 p.

Hashimoto, T. and Y. Maniwa, Study of reflection loss of ultrasonic millimetre wave on fish
1956 body. Tech.Rep.Fish.Boat Tokyo, (8):113-8

Haslett, R.W.G., Determination of the acoustic back-scattering patterns and gross sections
1962 of fish. Br.J.Appl.Phys., 13:349-57

___________, Acoustic echoes from targets under water. In Underwater acoustics, edited by
1970 R.W.B. Stephens. London, Wiley - Interscience, pp.129-99

___________, Automatic plotting of polar diagrams of target strength of fish in roll,
1977 pitch and yaw. Rapp.P.-V.Réun.CIEM, 170:74-81

Johannesson, K.A. and G.P. Losse, Methodology of acoustic estimations of fish abundance in
1977 some UNDP/FAO resource survey projects. Rapp.P.-V.Réun.CIEM, 170:296-318

Johannesson, K. and R. Vilchez, Application and some results of echo-integration methods in
1981 monitoring Peruvian anchovy resources. In Meeting on hydroacoustical methods for the estimation of marine fish populations, 25-29 June, 1979. Vol. 2. Contributed papers, discussions and comments, edited by J.B. Suomala. Cambridge, Mass., Charles Stark Draper Laboratory, pp.766-816

Love, R.H., Dorsal aspect target strength of an individual fish. J.Acoust.Soc.Am., 49(2):
1970 816-23

Midttun, L. and O. Nakken, On acoustic identification, sizing and abundance estimation of
1971 fish. Fiskeridir.Skr.(Havunders.), (16):36-48

Nakken, O. and K. Olsen, Target strength measurements of fish. Rapp.P.-V.Réun.CIEM, 170:
1977 52-69

Rijavec, L. and J. Burczynski (eds), Phase II - Technical report no. 2. Calibration of
1977 hydroacoustic equipment on board R.V. RASTRELLIGER (March-April 1977). UNDP/FAO Pelagic Fishery Investigation Project on the Southwest Coast of India, Cochin. Rome, FAO, IND/75/038:52 p.

SIMRAD, SIMRAD Echo integrator QM operation and maintenance. SIMRAD Publ.Oslo, (P547E):
1975 pag.var. and supplement C802E

Urick, J.R., Principles of underwater sound for engineers. New York, McGraw Hill Book Co.,
1975 384 p.

Yudanov, K.I., A.A. Jankov and O.S. Shatoba. Reflection properties of industrial fish
1966 species of the north basin. Rybn.Khoz., (12):57-60 (in Russian)

APPENDIX I

PLANE AND SOLID ANGLE

1. A Plane Angle

A plane angle is formed when two straight lines meet; these are called the "arms" of the angle. The angle (θ or ϕ) measures the difference in direction between the two arms (Figure 1). A plane angle (θ) can also be formed by the rotation of a ray (oriented line) around a fixed point called the vertex (point 'O' on Figure 2).

All methods of measuring plane angles are based on a division of the circumference. Since there is a proportional relationship between the circumference L_c and the radius r ($L_c = 2\pi r$) the size of an angle can be measured in terms of the ratio between an arc and the radius. Angular measures are dimensionless, but have names.

Two systems of measuring plane angles are in common use: degrees and radians. In order to distinguish in which system a given angle is measured, let us denote it as follows:

θ° - when an angle is measured in degrees $[^\circ]$

$\hat{\theta}$ - when an angle is measured in radians $[rd]$

1.1 A Degree

A degree is an angle subtended by an arc of a circle having a length equal to $^1/_{360}$ of the circumference. In this system, therefore, there are 360° in a circle.

1.2 A Radian

A radian is an angle subtended by an arc of a circle having a length equal to the radius of the circle ($L = r$), (Figure 3). The symbol for a radian is $[rd]$. Since the circumference of a circle has a length 2π times the radius ($L_c = 2\pi r$) there are 2π radians in a circle. The angle subtended by an arc of length L of a circle of radius r is simply $\hat{\theta} = \frac{L}{r}\,[rd]$.

Since the angle of complete rotation corresponds to $2\pi\,[rd]$ or to 360° (Figure 4), and any angle $\hat{\theta} = \frac{L}{r}\,[rd]$ corresponds to some equivalent in degrees θ°, we can write the proportion:

$$\frac{2\pi}{\hat{\theta}} = \frac{360^\circ}{\theta^\circ}$$

Therefore for a certain angle given in degrees, we can calculate its equivalent in radians as follows:

$$\hat{\theta} = \frac{2\pi}{360}\,\theta^\circ$$

e.g.,

$$\theta^\circ = 360^\circ \rightarrow \hat{\theta} = 2\pi\,[rd]$$

$$\theta^\circ = 180^\circ \rightarrow \hat{\theta} = \pi\,[rd]$$

$$\theta^\circ = 90^\circ \rightarrow \hat{\theta} = \frac{\pi}{2}\,[rd]$$

or vice versa as:

$$\theta^{o} = \frac{360}{2\pi}\hat{\theta}$$

$$\text{e.g.,} \quad \hat{\theta} = 1[rd] \rightarrow \theta^{o} = 57.295^{o}$$

1.3 An Arc Length

The length of an arc of circle "L", formed by the rotation of a radius of length "r" through a given angle ($\hat{\theta}$), is by the definition of $\hat{\theta}$ equal to:

$$L = r\hat{\theta}$$

2. A Solid Angle

The concept of a solid cone angle is an extension of the radian measure of a plane angle into three dimensions.

If we rotate the (x,y) plane with the plane angle θ on it around the (x) axis, as shown in Figure 5, we will obtain the three dimensional space (x,y,z) with the solids shown in Figure 6. The complete rotation corresponds to the plane angle $\hat{\phi} = 2\pi[rd]$ or $\phi^{o} = 360^{o}$.

During rotation the arc sweeps part of the surface of a sphere, and the radius "r" (which forms the plane angle θ with the (x) axis) describes the surface of a cone in space. The cone subtends the area "S" on the spherical surface.

The solid cone angle "Ω" is defined by the relationship between the area S and the radius r. Like a plane angle, a solid angle is measured in dimensionless units, called steradians.

2.1 A Steradian

A steradian is a solid angle subtended by part of a spherical surface which is equal in area to the square of the radius of the sphere ($S = r^2$). The symbol for a steradian is [sr]. Since the surface area of a sphere is $4\pi r^2$, there are 4π steradians in the sphere.

The solid angles (Ω) corresponding to the half angles ($\hat{\theta}$) of the radial cross-section of the corresponding cones can be calculated as follows:

A complete sphere $\Omega = 4\pi\ [sr] \rightarrow$ half a circumference $\hat{\theta} = \pi\ [rd]$

Half a sphere $\Omega = 2\pi\ [sr] \rightarrow$ ¼ of a circumference $\hat{\theta} = \frac{\pi}{2}\ [rd]$

Others $\Omega\ [sr] \rightarrow 2\pi\ (1 - \cos\hat{\theta})\ [rd]$ for $\hat{\theta} \leqslant \frac{\pi}{2}$

2.2 The Spherical Surface Area of a Cone

The spherical surface area, at distance "r" from the vertex corresponding to the given solid angle "Ω" can be expressed as:

$$\int_{s} ds = r^2 \int_{\Omega} d\Omega$$

or,

$$S = r^2\,\Omega$$

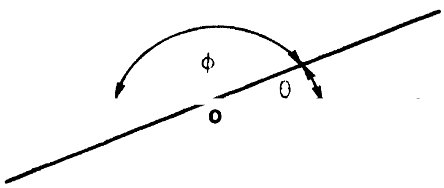


Fig. 1

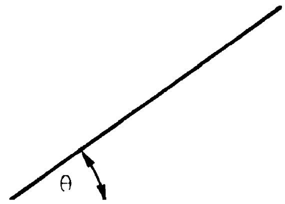


Fig. 2

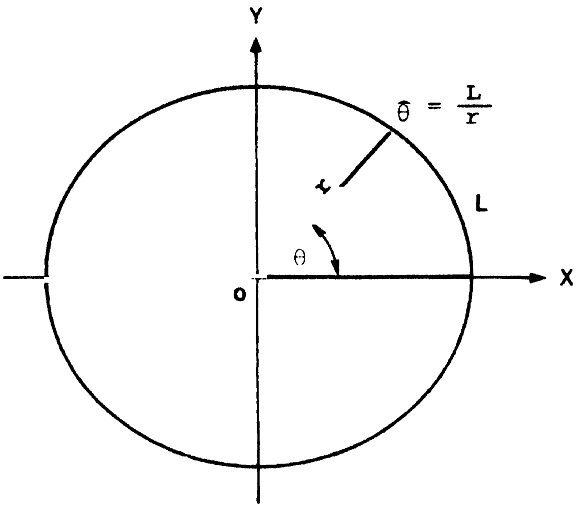


Fig. 3

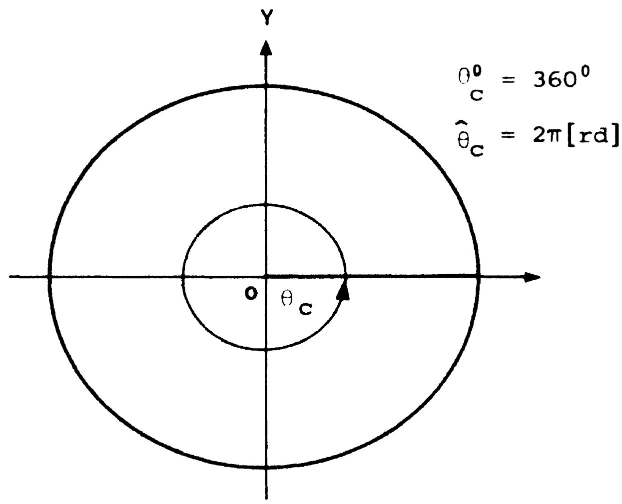


Fig. 4

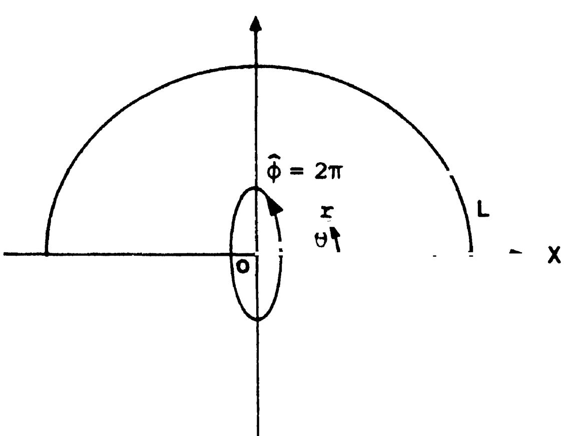


Fig. 5

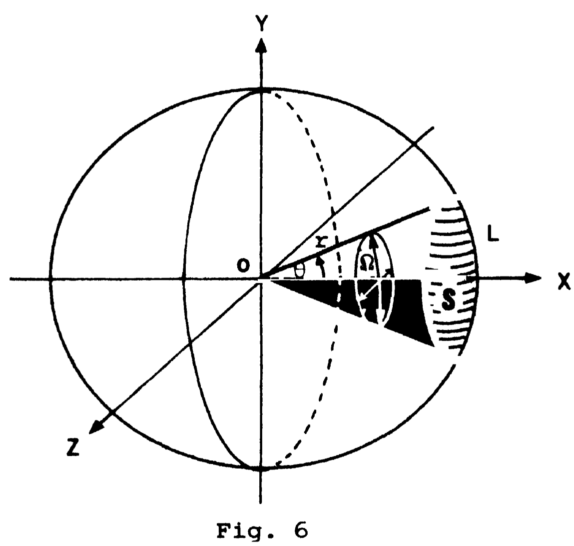


Fig. 6

APPENDIX II

DECIBELS

The values of sound intensity and other parameters of an acoustic field vary over wide ranges. Therefore, for convenience of calculations, logarithmic units called decibels (dB) are used, which permit that instead of multiplying and dividing large values of variables we can add and subtract their decibel equivalents.

The intensity of sound I_1 at a given point in the acoustic field can be measured by referring it to a standard value of intensity I_{st}1/:

$$n = \frac{I_1}{I_{st}}$$

Instead of expressing the ratio of the above two intensities arithmetically, it is customary to report ten times the common logarithm2/, or 10 log n:

$$N = 10 \log n = 10 \log I_1 - 10 \log I_{st}$$

The quantity N is then the intensity level I_1, in decibel units, referred to a standard intensity of I_{st}, for example the intensity of a sound wave is 10,000 times larger than the intensity of a plane wave of pressure 1μPa, the intensity level will be: 10 log 10,000 - 10 log 1 = 40 - 0 = 40 (dB ref. 1μPa) or (dB//1μPa). The reference levels here 1μPa, is written in order to make clear to which standard the calculated number of decibels is referred. It should be emphasized that in acoustics, decibels measure sound intensity, i.e. power density, and the sign (dB//1μPa) means the number of decibels referred to the <u>intensity</u> of a sound wave, that has an rms pressure of 1μPa.

If we have a more sophisticated equation, for example:

$$m = \frac{I_1}{I_{st}} AB^C$$

we can express it in decibels as follows:

$$M = 10 \log m = 10 \log I_1 - 10 \log I_{st} + 10 \log A + C\ 10 \log B \text{ (dB)}$$

The ratio value m can be recalculated by using its decibel equivalent M as:

$$m = \text{Antilog} \frac{M}{10} = 10^{\frac{M}{10}}$$

This procedure is very often used in practice for calculating the decibel equivalent of algebraic equations.

The tables below show some ratios of intensities and the corresponding values in decibels.

1/ The new standard intensity in underwater acoustics is the intensity of a plane wave having an rms pressure equal to 1 micropascal (μPa). The old standard intensity was that of a plane wave having an rms pressure equal to 1 dyn/cm^2 = 1 μBar (1 dyne per square cm equals 1 microbar), 1 μPa = 10^{-5} dyn/cm^2.

2/ log n = $\log_{10} n$ is the decimal logarithm of the magnitude n.

Table 1

Intensity ratio	$\frac{I_1}{I_2}$	0.0001	0.001	0.01	0.1	1	10	100	1000	10000
Decibels	$10 \log \frac{I_1}{I_2}$	-40	-30	-20	-10	0	10	20	30	40

Table 2

0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	2	3	4	5	6	7	8	9	10
-10	-6.99	-5.23	-3.98	-3.01	-2.22	-1.55	-0.97	-0.46	0	3	4.8	6	7	7.8	8.5	9	9.5	10

APPENDIX III

BEAM-FORMING OF A TRANSDUCER

Suppose two point sources are vibrating at the same frequency (Figure 1). The resultant sound wave in a given point of the acoustic field is the product of both sources. If the distance between the two sources is equal to the wave length (λ) or to any multiple of the wave length (2λ, 3λ, ... etc.), the sound waves transmitted along the line connecting the two sources will be in phase and therefore will reinforce each other (Figure 1a). If the distance between the two sources is equal to half the wave length

$$(\frac{\lambda}{2}),$$

or to any odd multiple of this value

$$(\frac{3}{2}\lambda,\ \frac{5}{2}\lambda,\ \ldots\ \text{etc.}),$$

the sound waves transmitted along the line connecting the two sources will be in opposite phases and both waves neutralize each other. Therefore the sound wave produced in total is equal to zero at any point of the acoustic field (Figure 1b).

The total sound field around two sources of sound is portrayed in Figure 1c. In the directions denoted by θ_m, the sound waves are in the same phase, while in the directions denoted by θ_{min}, they are in the opposite phase.

The radiating face of a transducer can be considered as a surface consisting of many point sources. The sound waves generated by the point sources interfere with each other, and the sound intensity varies with direction. The sound waves are in phase in the direction perpendicular to the transducer's radiating face which causes the maximum intensity on this direction. The intensity gradually decreases with increase of the angle θ, according to the wave length and the size of the transducer, which determines the directivity pattern of the transducer (Figure 10, Section 2.4.1).

However, the directivity pattern is formed only beyond a certain range from the transducer, i.e. in the "far field" of the transducer, where the effect of rapid changes of sound intensity with range and direction due to interference is negligible. Near the transducer, i.e. in the "near field", the sound intensity varies rapidly with range and bearing due to interference. In other words, the intensities at two points separated by a distance comparable to the wave length can be quite different. Far from the transducer the sound field is "stable", and the sound intensity varies with range and direction according to the transducer's directivity pattern and propagation laws.

The range of the near field can be calculated from the formula:

$$R_{nf} \approx \frac{S}{\lambda}$$

where, S = area of the radiating face of the transducer

λ = wave length

A more detailed explanation of the beam forming of the transducers and the far field and near field effect can be found in textbooks of acoustics (e.g. Urick, 1975; Clay and Medwin, 1977).

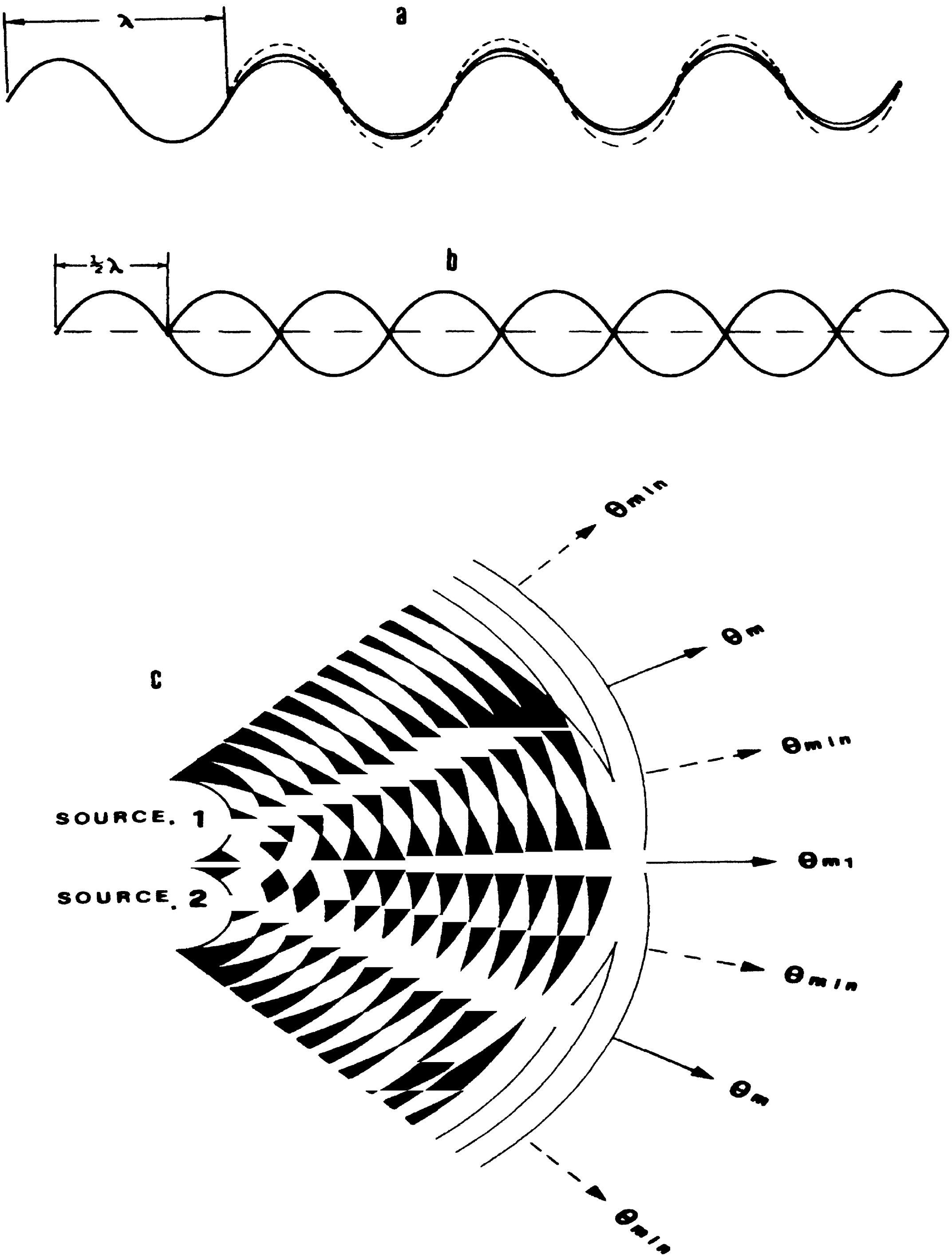


Figure 1 Schematic illustration of interference between sound waves originating from two sound sources (reproduction from Forbes and Nakken, 1972)

(a) sound waves in phase

(b) sound waves in opposite phase

(c) the sound field around two sources

APPENDIX IV

AVERAGING BY INTEGRATION

If we have n values L_1, L_2, ... L_n of the variate L length (e.g. the length of n individual fishes), the mean value $\bar{L}$ of the distribution as shown in Figure 1 is given by:

$$\bar{L} = \frac{1}{n} \sum_1^n L_n$$

Similarly, if a magnitude varies in time, e.g. a variable voltage u (t), its average value for a given period of time ΔT can be expressed (Figure 2) as follows:

$$\bar{u} = \frac{1}{\Delta T} \int_{\Delta T} u(t)dt$$

where, $\int_{\Delta T} u(t)dt$ = is the integral of the variable u(t), over a period of time ΔT

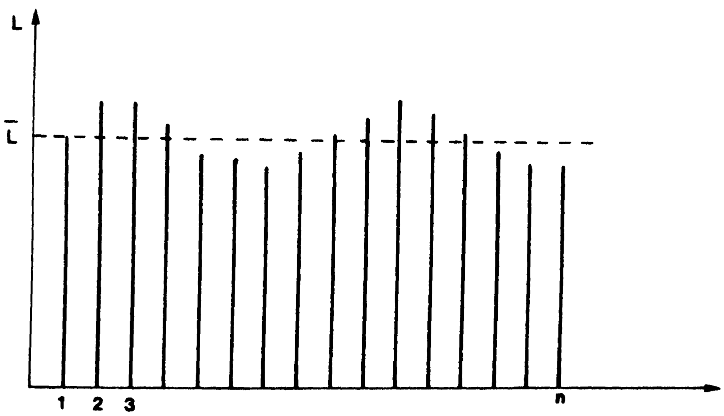


Figure 1

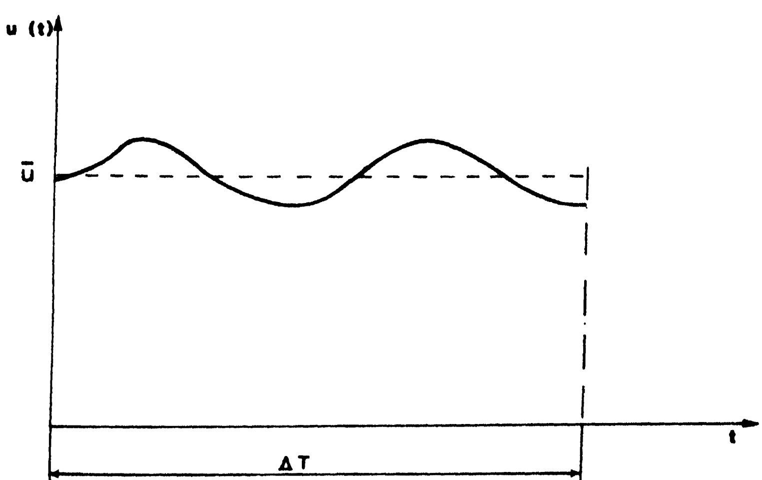


Figure 2

APPENDIX V

PERFORMANCE CHECK OF THE ECHO INTEGRATOR QM-MK II AND THE ECHOSOUNDER EK-120

(Example from the UNDP/FAO Pelagic Fishery Investigation Project on the Southwest Coast of India, Phase II. Technical Report No. 2 (L. Rijavec and J. Burczynski (eds) 1977)

The values of SL, VR, NL, M and S are given in "old units"(see footnote 1/ on page 73).

1. Echo Integrator QM-MK II

The test has been carried out acccrding to Simrad Publication P574E "Simrad Echo Integrator QM Operation and Maintenance". Supplement C802E, page 4.

Settings of the Echo Integrator

Gain	0 dB
Threshold	0
Operate/Test switch	TEST
Depth	50 m
Interval	30 m
Normal/10 X switch	NORM
Mode	3
Speed compensation	MAN
Speed	10 Knots

Settings of the Echosounder EK-120 Connected to the Integrator

Test/Operate switch	TEST
Range	0-125 m and 0-250 m

The Echo Integrator Used for the Calibration on Live Fish

For both ranges of echosounder EK-120, the echo integrator recorder reached 45 mm deflection in both channels after 6 minutes.

The Echo Integrator Used for Calibration on Standard Target (stainless steel sphere)

The echo integrator recorder reached, after 6 minutes, 46 mm in Channel A and 48 mm in Channel B.

2. Echosounder EK-120

The test has been carried out according to SIMRAD Publication C738E "Performance Measurements on Simrad Scientific Sounder, EK-120".

(a) Transducer impedance (measured across transducer's terminals of the echosounder EK-120)

Vessel's transducer

F [kHz]	116.6	116.8	117.6	120	124
Z [Ω]	50	52	47	70	29

External transducer

F [kHz]	115.9	120	123	138
Z [Ω]	40	98	200	60

(b) Transmitter

Transmitter operating frequency: 119.9 kHz

Transmitter's power across transducer's terminals:

Transducer	External transducer		Vessel's transducer	
Power setting	1/1	1/10	1/1	1/10
U_{pp} $[V_{pp}]$	750	350	750	350
$Z_{119.9}$ $[\Omega]$	95	95	71	71
Power $P = \frac{U^2_{pp}}{8\ Z}$ $[W]$	740	161	990	216

Voltage across "TEST" connector: 32 V_{pp} for power setting 1/1
11.4 V_{pp} for power setting 1/10

Pulse length:

Selector position				
Pulse duration [ms]:	0.14	0.3	0.52	1

(c) Source level (SL)

	External transducer	Vessel's transducer
Pulse travel time t [ms]	3.0	3.0
Distance transducer/ hydrophone r = 1.47 t [m]	4.41	4.41 (4.5) 1/
Range correction 20 log r [dB]	12.89	12.89

Hydrophone Brüdel & Kjear type 5739 No. 641059

Hydrophone receiving voltage response M = -115.3[dB//1 V per μ Bar]

Hydrophone receiving voltage response with extension cable

M + d = -117.4[dB// 1 V per μ Bar]

Sea temperature 29.5°C.

1/ The distance given in brackets was measured by tape.

	External transducer		Vessel's transducer	
Power selector	1/1	1/10	1/1	1/10
Oscilloscope reading U_{pp} $[V_{pp}]$	1.28	0.47	1.25	0.41
$U_{rms} = \frac{U_{pp}}{2\sqrt{2}}$ $[V]$	0.45	0.17	0.44	0.14
20 log U_{rms} [dB//1 V_{rms}]	-6.86	-15.58	-7.09	-16.78
M + d [dB//1 V per μBar]	-117.4	-117.4	-117.4	-117.4
20 log r [dB//1 m]	12.89	12.89	12.89	12.89
SL [dB//1 μBar, ref. 1 m]	123.40	114.71	123.2	113.5

$$SL = 20 \log U_{rms} - (M + d) + 20 \log r$$

(d) Receiver gain (wide bandwidth)

Attenuation of the attenuator D = 49.2 dB

Receiver gain RG = 49.2 + 35.4 = 84.6 dB

TVG & Gain selector in position -20 dB gives -18 dB of attenuation

(e) System's receiving voltage response (VR) for WIDE BANDWIDTH of the receiver

Hydrophone transmitting voltage response S = 36.5 [dB//1 μBar per V, ref. 1 m]

Range correction 20 log r as in (c)

System's receiving voltage response: $VR = UL_{out} - G - (S + UL_{hydr} - 20 \log r)$

UL_{out} - Voltage level on "Calibrated Output" terminal of the echosounder [dB//1 V_{rms}]

G - Settings of TVG and GAIN selector [dB]

UL_{hydr} - Voltage level across hydrophone [dB//1 V_{rms}]

	External transducer		Vessel's transducer	
G (setting of TVG & GAIN)	0	-20	0	-20
UL_{out} [dB//1 V_{rms}]	0	-18.5	0	-18
S [dB// 1 μBar, ref. 1 m]	36.5	36.5	36.5	36.5
UL_{hydr} [dB//1 V_{rms}]	-23	-23	-21.2	-21.2
20 log r [dB//1 m]	12.89	12.89	12.89	12.89
VR [dB// 1 V per μBar]	-0.61	0.89	-2.41	-0.41

(f) Receiver bandwidth (without transducer)

f kHz:	115.3	115.9	118.0	120.7	122.6	124.4	WIDE
UL_{output} dB:	-3	+1	-2.2	0	+0.5	-3	BANDWIDTH

f kHz	115.3	116.0	117.7	120.7	122.7	123.4	124.4	NARROW
UL_{output} dB	-3	+1	-2.3	0	-0.6	-0.3	-3	BANDWIDTH

(g) Noise level for external transducer (for stopped engine of vessel)

Noise level $NL = VR + UL_{noise}$ [dB]

UL_{noise} noise level on "Calibrated Output" terminals of the echosounder [dB//1 V]

For wide bandwidth of receiver NL = -0.6 - 41 = -41.6 dB//1 μBar

For narrow bandwidth of receiver NL = -0.6 - 48 = -48.6 dB//1 μBar

(h) Noise level for vessel's transducer (for narrow bandwidth of the receiver)

Propeller	RPM	Engine Stopped	380	220	220	220	230	240	260	300
Propeller	Pitch		105	0	0	0	0	0	0	0
U_{out}	[dB//1 V]	-45	-24	-50	-52	-48	-46	-48	-48	-49
NL	[dB//1 μBar]	-42.8	-21.8	-44.8	-49.8	-45.8	-45.8	-45.8	-45.8	-46.8

Propeller	RPM	375	375	375	375	375	375	375	375	375
Propeller	Pitch	0	10	20	30	40	50	60	70	80
U_{out}	[dB//1 V]	-49	-49	-40	-43	-39	-37	-39	-33	-26
NL	[dB//1 μBar]	-46.8	-46.8	-37.8	-36.8	-36.8	-34.8	-36.8	-30.8	-23.8

Propeller	RPM	375	375	375	375
Propeller	Pitch	90	100	105	85
U_{out}	[dB//1 V]	-23	-23	-21	-24
NL	[dB//1 μBar]	-20.8	-20.8	-18.8	-21.8

(i) TVG (Time Variable Gain) characteristics

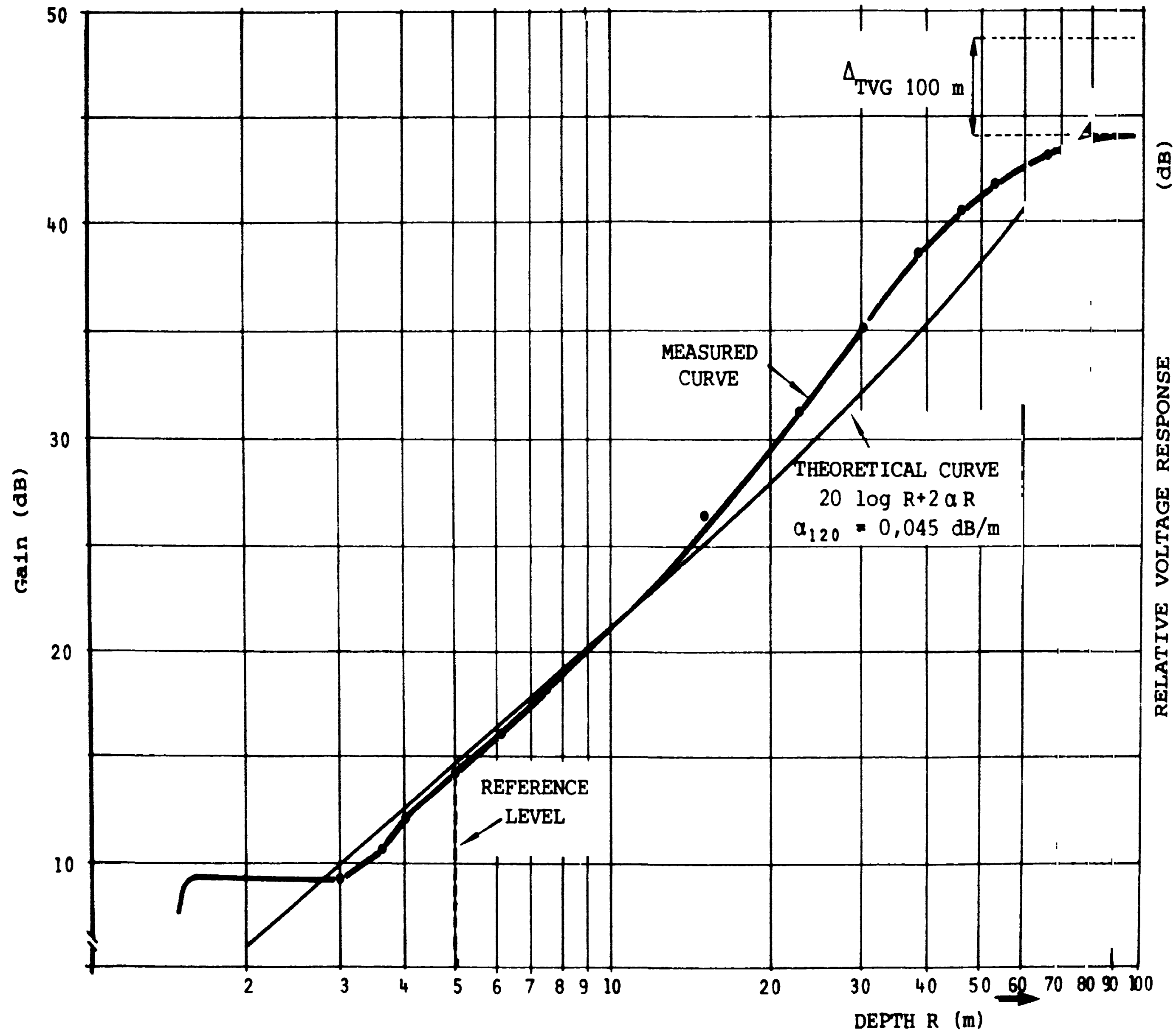
The theoretical and measured TVG characteristics of the echosounder are shown in Figure 1.

Because of the observed deviations between the theoretical and measured TVG curve at different depths, the sample echo integrator values obtained during the survey were adjusted by multiplying them by a correction factor, k_{TVG}, corresponding to the depth at which the fish were recorded.

The correction factor was calculated as follows:

$$k_{TVG} = \text{Antilog} \frac{1}{10} \left[(20 \log R + 2\alpha R) - f\ (TVG) \right]$$

where $(20 \log R + 2\alpha R)$ is the theoretical TVG curve and f (TVG) are the measured TVG characteristics (see Figure 2).



e 1 eoretica and asured TVG character cs he echos er

3. Measurements with Standard Target

External transducer	Echo integrator deflection	Channel A M [mm]	18	15	15	21.5	29	3	4	4	17	15
		Channel B M [mm]	19	15	15	22.0	30	4	4	4	18	16
	Voltage on "CAL.OUTPUT" of echosounder $U_{pp}[V_{pp}]$			8		9.4	10		4			8
	Remarks		Strong current			No current			Strong current			
Vessel's transducer	Echo integrator deflection	Channel A M [mm]	8	8.5	10	15	17	17	9	8	8	8
		Channel B M [mm]	9	9.5	11	18	19	19	10	9	9	9
	Voltage on "CAL.OUTPUT" of echosounder $U_{pp}[V_{pp}]$			5		8	8.5	8.5			5	
	Remarks		Strong current			No current			Strong current			

M - integrator deflection per EDSU

Standard target: stainless steel sphere,
TS = -36.4 dB,
Diameter 6 cm

Distance between sphere and transducer: 5.5 m

Settings of instruments: EK-120 - Range: 0-125 m
TVG & Gain: 20 log R/0 dB
Power: 1/1
Band width & pulse length: 2/WIDE (0.3 ms)

QM-MK II - Gain: 0 dB x 10
Threshold: 0
Depth: 5 m
Interval: 1 m
Speed compensation: MAN
Speed: 10 knots

The echo integrator deflection was recorded every 6 minutes, which corresponds to steaming one EDSU (Elementary Distance Sampling Unit) of 1 nautical mile.

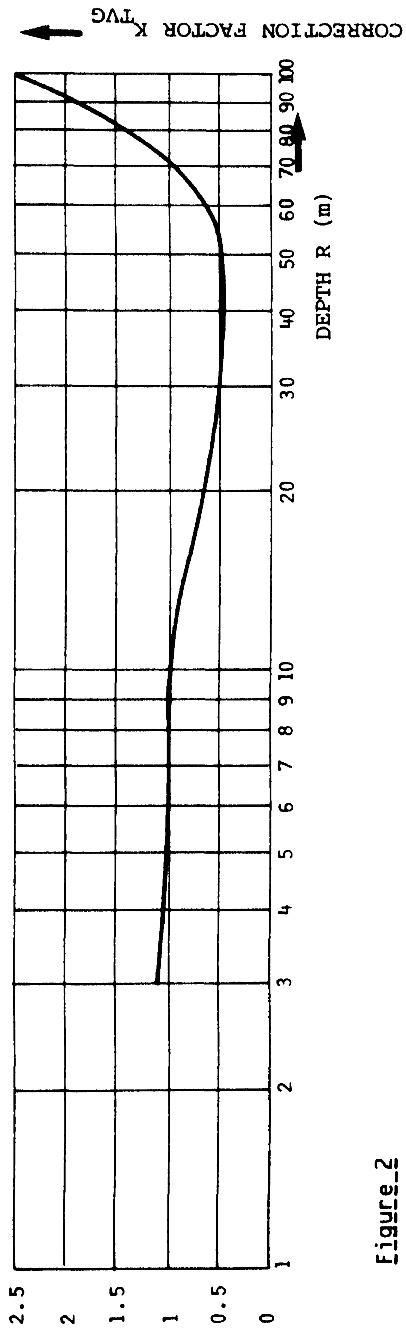

CORRECTION FACTOR K TVG
DEPTH R (m)
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
2.5
2
1.5
1
0.5
0

Figure 2

4. Settings of Instruments During Calibration Experiments

1. Settings of the Echosounder EK-120

Range:	0-125 m
TVG & Gain:	20 log R/-20 dB
Power:	1/1
Bandwidth & pulse length:	2/WIDE (0.3 ms)

2. Settings of the Echo Integrator QM-MK II

Gain:	10 dB x 10
Threshold:	0
Depth:	5 m
Interval:	1 m
Speed compensation:	MAN
Speed:	10 knots

The echo integrator deflection was recorded every 6 minutes, which corresponds to steaming one EDSU (Elementary Distance Sampling Unit) of 1 nautical mile.

3. Reference Level

The echo integrator deflection values are referred to the following standard settings used during the survey:

Echosounder EK-120

TVG & Gain:	20 log R/0 dB
Power:	1/1
Bandwidth & pulse length:	2/WIDE (0.3 ms)

Echo integrator QM-MK II

Gain:	20 dB/ x 1 (NORM)

5. Inter-Calibration of Transducers

The ratio of calibration constant values for the vessel and external transducer can be expressed as follows:

$$k = \frac{C_v^x}{C_e^x} = \frac{\frac{\Delta d}{\Delta M_v}}{\frac{\Delta d}{\Delta M_e}}$$

where,

C_v^x = calibration constant for the vessel's transducer

C_e^x = calibration constant for the external transducer

Δd = increment of fish density

ΔM_v = increment of integrator deflection for the vessel's transducer

ΔM_e = increment of integrator deflection for the external transducer

When measuring the integrator deflection from a standard target for both transducers, the ratio of calibration constant will be:

$$k = \frac{M_e}{M_v}$$

where,

M_e = integrator deflection for EDSU for the external transducer

M_v = integrator deflection for EDSU for the vessel's transducer

During calibration experiments with the standard target, strong currents were observed (see page 84) which diverted the sphere from the centre of the transducer's beam; the maximum values of the integrator deflection which correspond to the position of the sphere close to the centre of the transducer beam width were therefore taken into account for the calculation of k. The ratio for the calibration constant values of the vessel's transducer and external transducer are shown below:

For Channel A: $k = \frac{29}{17} = 1.71$

For Channel B: $k = \frac{30}{19} = 1.58$

The value of k can also be calculated from the parameters of the acoustic instrument.

The calibration constant can be expressed as follows (see Section 3.4):

$$C^x = c_i \, c_f$$

where,

c_i = instrument constant

c_f = fish constant

The instrument constant is given as:

$$c_i = \text{Antilog}\left[\frac{1}{10}\left(-SL - VR + 20 \log R + 2\alpha R - 10 \log \frac{c\tau}{2} - 10 \log \psi - A + V_o\right)\right]$$

where,

SL = source level (dB//1 μBar, ref. 1 m)

VR = voltage response (dB//1 V per μ Bar)

= one-way spherical spreading
+ two-way absorption (dB)

τ = pulse length (ms)

c = sound wave velocity (m/s)

ψ = equivalent beam width of the transducer (dB//ster)

A = gain of instruments (dB)

V_o = normalized value of an average output signal of the echosounder in dB, corresponding to the echo integrator deflection unit (M = 1 mm) for the depth interval unit (ΔR = 1 m)

The calibration constant ratio can then be expressed as follows:

$$k = \frac{c_{iv}}{c_{ie}} = \text{Antilog}\left[\frac{1}{10}\left(-SL_v - VR_v + SL_e + VR_e\right)\right]$$

where,

SL_v = sourve level for vessel's transducer

VR_v = voltage response for vessel's transducer

SL_e = source level for external transducer

VR_e = voltage response for external transducer

When substituting values of source level and voltage response for both transducers, as in Appendix II, into the above formula, the calibration constant ratio will be:

$$k = \text{Antilog}\left[\frac{1}{10}\left(-\ 123.2 + 2.41 + 123.4 - 0.61\right)\right] = 1.58$$

The above value of k corresponds to the one obtained by direct inter-calibration on the standard target for Channel B of the integrator, and it is used for further calculations.

The calibration constant for the vessel's transducer will then be:

$$C_v = k\ C_e$$

Finally, the calibration constant for the vessel's transducer to be used for the survey for the settings (EK: 20 log r/-20 dB; QM: 10 dB x 10) will be as follows:

(1) For mixed pelagic species:

$$C_{v(-20/10x10)} = 1.58 \times 51 = 80.6 \quad (t/n\,mi^2/mm, \text{ ref. } 1\ n\,mi)$$

(2) For mackerels:

$$C_{v(-20/10x10)} = 1.58 \times 171 = 270 \quad (t/n\,mi^2/mm, \text{ ref. } 1\ n\,mi)$$

SELECTED LIST OF FAO PUBLICATIONS ON FISHERY RESOURCE APPRAISAL METHODOLOGY

FAO publications on scientific aspects of fisheries are issued in three main series:

(a) FAO Manuals on Fisheries Science. There are major priced publications.

(b) FAO Fisheries Technical Papers, which are the definite repository for most papers on technical subjects.

(c) FAO Fisheries Circulars, which are used as a repository for preliminary studies that may be reissued as Technical Papers in definite form.

Some other publications from regional bodies are also included. These, however, may not be available as readily as the main series. The available priced publications and main documents can be obtained on request from: the Distribution and Sales Unit, FAO, Via delle Terme di Caracalla, Rome 00100. A list of FAO Fisheries Department publications covering the years 1948-1978 is published as FAO Fisheries Circular (100) Rev.3.

1. Fishery Biology

Holden, M.J. and D.F.S. Raitt (eds), Manual of fishery science. Part 2. Methods of resource 1974 investigations and their application. FAO Fish.Tech.Pap., (115)Rev.1:214 p. (E,F,S)

Kesteven, G.L., Manual of fishery science. Part 1. An introduction to fisheries science. FAO 1973 Fish.Tech.Pap., (118):43 p. (E,F,S)

Laevastu, T., Manual of methods in fisheries biology. FAO Man.Fish.Sci., (1) 10 Fasc. (E,F,S) 1965

Tomczak, G.H., Environmental analyses in marine fisheries research. FAO Fish.Tech.Pap., (170): 1977 141 p.

2. Stock Assessment and Fishery Management

Alverson, D.L. (ed.), Manual of methods for fisheries resource survey and appraisal. Part 1. Survey 1971 and charting of fisheries resources. FAO Fish.Tech.Pap., (102):80 p.

Beverton, R.J.H. and S.J. Holt, Manual of methods for fish stock assessment. Tables of yield 1966 functions. FAO Fish.Tech.Pap., (38)Rev.1:67 p. (E,F,S)

CIDA/FAO/CECAF, Selected lectures from the CIDA/FAO/CECAF seminar on fishery resource 1980 evaluation. Casablanca, Morocco, 6-24 March 1978.

Csirke, J., Introduccion a la dinamica de poblaciones de peces. FAO Fish.Tech.Pap., (192):82 p. 1980

AO, 1976 Monitoring of fish stock abundance: the use of catch and effort data. A report of the ACMRR Working Party on fishing effort and monitoring of fish stock abundance. FAO Fish.Tech.Pap., (155):101 p.

________, 1978 Some scientific problems of multispecies fisheries. Report of the expert consultation on management of multispecies fisheries, Rome, Italy, 20-23 September 1977. FAO Fish.Tech.Pap., (181):42 p.

________, 1978a Models for fish stock assessment. FAO Fish.Circ., (701):122 p. (E,F)

;arcia, S. and L. Le Reste, 1981 Life cycles, dynamics, exploitation and management of coastal penaeid shrimp stocks. FAO Fish.Tech.Pap., (203):215 p.

;ulland, J.A., 1969 Manual of methods for fish stock assessment. Part 1. Fish population analysis. FAO Man.Fish.Sci., (4):154 p. (E,F,S)

________, 1972 Guidelines for fishery management. Rome, FAO, Indian Ocean Programme, IOFC/DEV/74/36:84 p.

________, 1972a Some introductory guidelines to management of shrimp fisheries. Rome, FAO, Indian Ocean Programme, IOFC/DEV/72/24:12 p.

________, 1977 Goals and objectives of fishery management. FAO Fish.Tech.Pap., (166):14 p. (E,F,S)

________, 1980 Some problems of the management of shared stocks. FAO Fish.Tech.Pap., (206):22 p.

ones, R., 1976 The use of marking data in fish population analysis. FAO Fish.Tech.Pap., (153):42 p.

________, 1976a Mesh regulation in the demersal fisheries of the South China Sea area. Manila, South China Sea Fisheries Development and Coordinating Programme, SCS/76/WP/34

________, 1979 Materials and methods used in marking experiments in fishery research. FAO Fish. Tech.Pap., (190):133 p.

________, 1981 The use of length composition data in fish stock assessments (with notes on VPA and cohort analysis). FAO Fish.Circ., (734):55 p.

auly, D., 1980 A selection of simple methods for the assessment of tropical fish stocks. FAO Fish.Circ., (729):54 p.

ope, J.A. et al., 1975 Manual of methods for fish stock assessment. Part 3. Selectivity of fishing gear. FAO Fish.Tech.Pap., (41)Rev.1:46 p.

________, 1979 Stock assessment in multispecies fisheries with special reference to the trawl fishery in the Gulf of Thailand. Manila, South China Sea Fisheries Development and Coordinating Programme, SCS/DEV/79/19

3. Resources Surveys

Alverson, D.L., 1971 Field surveys and the survey and charting of resources. Rome, FAO, Indian Ocean Programme, IOFC/DEV/71/6:22 p.

Burczynski, J., 1982 Introduction to the use of sonar systems for estimating fish biomass. FAO Fish.Tech. Pap., (191)Rev.1:89 p.

Forbes, S.T. and O. Nakken (eds), 1972 Manual of methods for fisheries resource survey and appraisal. Part 2. The use of acoustic instruments for fish detection and abundance estimation. FAO Man.Fish.Sci., (5):138 p. (E,F,S)

Gulland, J.A., 1975 Manual of methods for fisheries resource survey and appraisal. Part 5. Objectives and basic methods. FAO Fish.Tech.Pap., (145):29 p.

Mackett, D.J., 1973 Manual of methods for fisheries resource survey and appraisal. Part 3. Standard methods and techniques for demersal fisheries resource surveys. FAO Fish.Tech.Pap., (124):39 p.

Saville, A. (ed.), 1977 Survey methods of appraising fishery resources. FAO Fish.Tech.Pap., (171):76 p. (E,F,S)

Smith, P.E. and S.L. Richardson, 1977 Standard techniques for pelagic fish egg and larva surveys. FAO Fish.Tech.Pap., (175):100 p. (E,S)

Ulltang, O., 1977 Methods of measuring stock abundance other than by the use of commercial catch and effort data. FAO Fish.Tech.Pap., (176):23 p. (E,F,S)

4. Fishery Statistics

Banerji, S.K., 1974 Frame surveys and associated sample survey designs for the assessment of marine fish landings. Rome, FAO, Indian Ocean Programme, IOFC/DEV/74/39:15 p.

__________, 1975 Improvement of national fishery statistics. Rome, FAO, Indian Ocean Programme, IOFC/DEV/75/41:15 p.

Bazigos, G.P., 1974 The design of fisheries statistical surveys - Inland waters. FAO Fish.Tech.Pap., (133):122 p. (E,F,S)

__________, 1974a Applied fishery statistics. FAO Fish.Tech.Pap., (135):164 p. (E,F,S)

__________, 1975 Applied fishery statistics: vectors and matrices. FAO Fish.Tech.Pap., (135) Suppl.1: 34 p. (F and S in preparation)

__________, 1976 The design of fisheries statistical surveys - inland waters. FAO Fish.Tech.Pap., (133) Suppl.1:46 p.

__________, 1977 Mathematics for fishery statisticians. FAO Fish.Tech.Pap., (169):183 p.

Brander, K., Guidelines for collection and compilation of fishery statistics. FAO Fish.Tech.Pap., 1975 (148):46 p.

FAO, The collection of catch and effort statistics. FAO Fish.Circ., (730):63 p.
1980

Gulland, J.A., Manual of sampling and statistical methods for fisheries biology. Part 1. Sampling 1966 methods. FAO Man.Fish.Sci., (3):87 p. (E,F,S,P)

Moller, F., Manual of methods in aquatic environmental research. Part 5. Statistical tests. FAO 1979 Fish.Tech.Pap., (182):131 p.

5. Inland Fisheries

Bhukaswan, T., Management of Asian reservoir fisheries. FAO Fish.Tech.Pap., (207):69 p.
1980

FAO, Comparative studies on freshwater fisheries. Report of a Workshop held at the Istituto Italiano 1980 di Idrobiologia. Pallanza, Italy, 4-8 September, 1978. FAO Fish.Tech.Pap., (198):46 p.

Welcomme, R.L., Fishery management in large rivers. FAO Fish.Tech.Pap., (194):60 p.
1979

Welcomme, R.L. and H.F. Henderson, Aspects of the management of inland waters for fisheries. FAO 1976 Fish.Tech.Pap., (161):40 p. (E,F,S)

No:11229

$$\begin{array}{r} 89+27 \\ \hline 116 \end{array}$$